Report No. NADC-91003-60

AD-A236 946

270 VOLT DIRECT CURRENT GENERATOR PERFORMANCE EVALUATION

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DECEMBER 1990

FINAL REPORT
Period Covering June 1990 to August 1990
Task No. W1355000A
Project No. 0
Work Unit No. MV900
Program Element No. 0604268N

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Prepared for
NAVAL AIR SYSTEMS COMMAND
Department of the Navy
Washington, DC 20361-0001

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release; Distribution is Unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NADC-91003-60	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Air Vehicle and Crew Systems Technology Department 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code) NAVAL AIR DEVELOPMENT CENTER Warminster, PA 18974-5000	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION NAVAL AIR SYSTEMS COMMAND 8b OFFICE SYMBOL (If applicable) AIR-53633	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code) Washington, DC 20361-0001	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO: 0604268N PROJECT NO: - TASK NO: W1355-000A WORK UNIT ACCESSION NO: MV900

11 TITLE (Include Security Classification)

270 Volt Direct Current Generator Performance Evaluation

12 PERSONAL AUTHOR(S)

Jenifer M. Shannon

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM 6/90 TO 8/90	1990 December	

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This docment presents the results of the testing of a 45KW, 270 VDC generator. Parameters measured include line voltage, field current, peak-to-peak ripple voltage, distortion spectrum, and transients due to both load application and load removal. The purpose of this testing was to provide a baseline of 270 VDC generator performance. The baseline data will be used as an input of the revision of MIL-STD-704D, the aircraft power quality specification. The performance of the generator under test exceeded expectations. The conclusion of this testing is that no significant problems should be encountered by generator vendors in their efforts to meet the new 270 VDC requirements set forth in MIL-STD-704E.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL Jenifer M. Shannon	22b TELEPHONE (Include Area Code) 215 441-7216	22c OFFICE SYMBOL 6012

DD Form 1473, JUN 86 Previous editions are obsolete SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603 Unclassified

FIGURES

TABLES

ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
dB	Decibels
GCU	Generator Control Unit
Hz	Hertz (cycles per second)
kHz	Kilohertz (x1000 cycle per second)
NADC	Naval Air Development Center
pf/ft	Picofarads/foot
rms	root mean square
rpm	Revolutions per minute
V	Volts
V p-p	Volts peak-to-peak
VDC	Volts Direct Current

270 VOLT DIRECT CURRENT GENERATOR PERFORMANCE EVALUATION

Background

Single channel testing was performed on the Lucas Aerospace 270 Volt DC generator #101 with Generator Control Unit (GCU) #103, during the second half of FY90. This testing was conducted in the George Tsaparas Laboratory at the Naval Air Development Center (NADC) by personnel from the Electrical and Flight Control Branch. Generator parameters recorded include line voltage, field current, peak-to-peak ripple voltage, distortion spectrum, and transients due to both load application and load removal. The load bank used in the testing was purely resistive.

The purpose of this testing was to provide a general insight to the capabilities of 270 Volt DC generators. MIL-STD-704D, reference (1), is a specification which defines aircraft power quality; this specification is currently being revised. The major changes in the 270 Volt DC section of this specification involve voltage ripple, distortion, and voltage transients. The new ripple and distortion criteria that will be incorporated into MIL-STD-704 were derived from theoretical calculations and experimental measurements. The derivation of this criteria is described in a white paper by Mr. Eric Speck from the Naval Air Test Center who is directly involved with the revision of MIL-STD-704. Excerpts from this paper describing the criteria are included in Appendix A. The new transient limits being considered are defined in AS-1831, reference (2). The distortion and ripple measurements taken during this testing were compared to the criteria established in Appendix A, and the transient measurements were compared to the limits of reference (2). Analysis of the test results will provide verification that 270 Volt DC generators will be capable of meeting the criteria of MIL-STD-704E.

The Lucas generator was a prototype model developed under contract #N62269-79-C-0226 for NADC per NADC-60-TS-7803, reference (3). The 45 KW generator is an oil-cooled, brushless machine with an internal full wave bridge rectifier. This generator does not

represent current state-of-the-art 270 Volt DC generator capabilities. Many advances in generator design, stronger magnetic materials, and new GCU and rectifier components have improved 270 Volt DC system performance since the Lucas generator was built. However, the performance of the Lucas generator can provide a baseline for comparison to present day generators. The overall performance of the Lucas generator was commendable; in many instances, its performance exceeded the requirements called out in the references.

General Performance

During all tests, the steady state line voltage of the generator was recorded. Steady state occurs after a sufficient period of time has passed following any transient that has occurred due to load switching or a change in generator speed. Steady state voltage is defined for 270 VDC by MIL-STD-704D as between 250 and 280 VDC. In Figure (1) the effect of speed and load on the line voltage is shown. The line voltage is well regulated (between 268 V and 270 V) with a load present. During the no load condition, regulation is still good, but the line voltage is higher than when a load is connected. At no load and increasing generator speed, the line voltage also increases. At 25% load, the line voltage followed the same pattern as it did with no load but at 2 to 3 volts less. At every other load condition (50%, 75%, 100%), during minimum generator speed, the line voltage was at its maximum; however, as the speed was increased to 13,000 rpm, the line voltage drops and then remains approximately the same for the remainder of the speed range.

The field current was also recorded throughout all testing. In Figure (2) the effect of speed and load on field current is shown. The field current consistently increases as the load is increased. As generator speed is increased, the field required to achieve output power is smaller; therefore, the field current decreases.

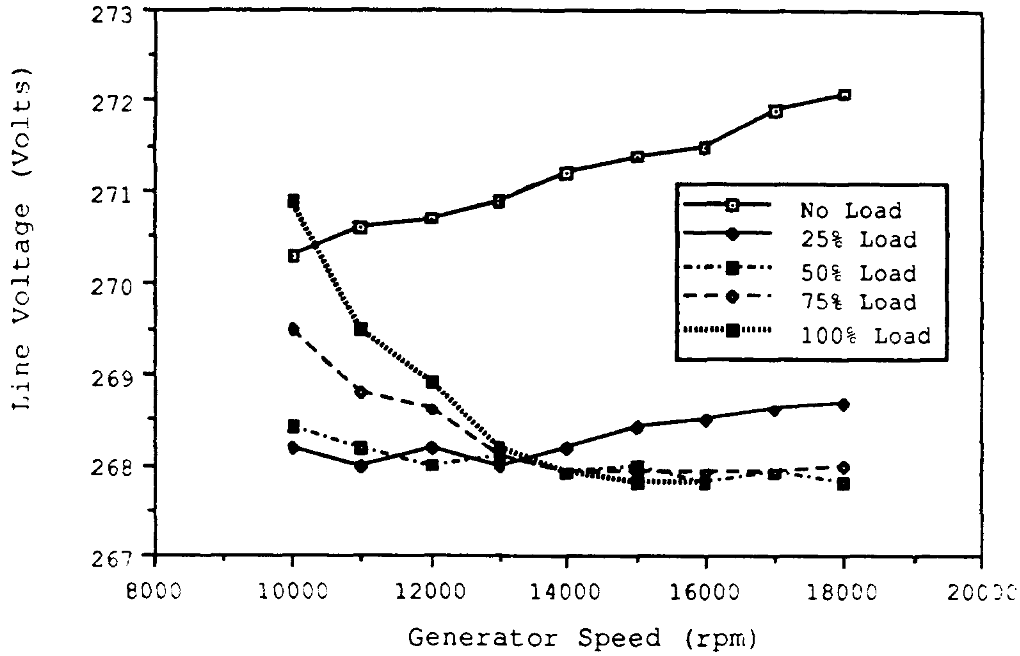


Figure 1. Effect of Speed & Load on Line Voltage

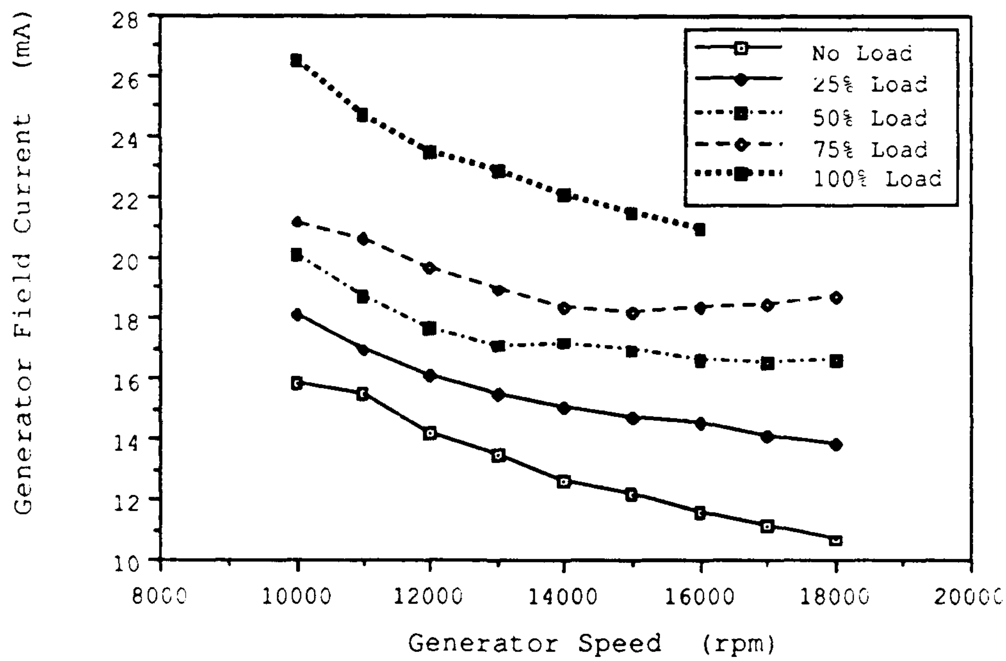


Figure 2. Effect of Speed & Load on Field Current

Ripple Measurements

Peak-to-peak ripple was measured at no load, 25%, 50%, 75% and 100% loads over the operating speed range of the generator. Approximately 10 peak-to-peak measurements were taken at each test condition; these numbers were then averaged to yield a more accurate representation of ripple. The mean ripple voltages are plotted in Figure (3) versus generator speed. For most test conditions, the ripple voltage was between 4.5 and 5.5 volts peak-to-peak. The worst case ripple, 7.7 V p-p, occurred at 75% load and 18,000 rpm. The overall average ripple was 4.7 V p-p.

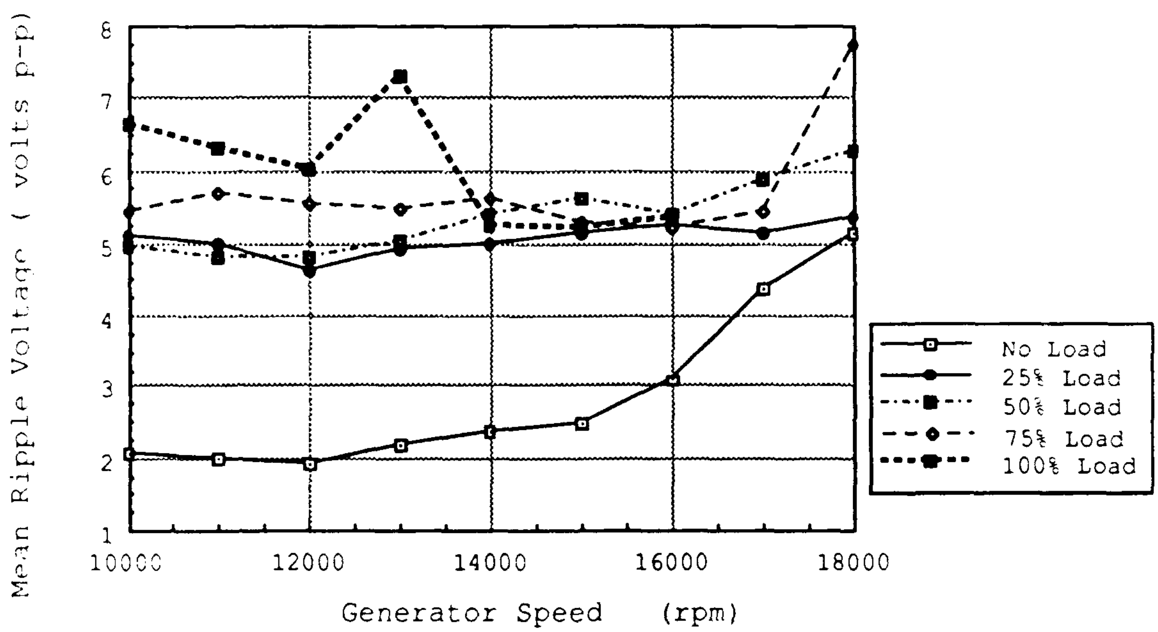


Figure 3. Peak-to-Peak Ripple Voltage

A separate test was performed to determine the effect of flat bus cable on power quality. Ripple measurements were recorded while a 50 foot No. 6 flat cable was connected to the generator output. It should be noted that the cable and connector were not flight qualified hardware. The flat bus used in this test

consisted of two thin insulated copper strips layered together. Some of the advantages of using flat bus over round wire in power systems include decreased inductance, increased capacitance and an inherent fault isolation property. The inherent fault isolation property is due to the magnetic field generated by the layered geometry of flat bus. During a fault, this magnetic field causes the conductors to separate at the point of a fault. The increased capacitance property is an effective means of reducing the ripple on the power bus. The specified capacitance of the flat cable is 8000 pf/ft. Therefore, the approximate capacitance of the cable used in this test is 0.4 microfarads.

In comparing the ripple measurements taken with the flat bus to those taken without the flat bus, a significant ripple voltage reduction is observed. At no load, the flat bus has no appreciable effect on ripple, since the ripple is already fairly low (See Figure 4). However, by attaching the flat bus to the generator, the ripple was reduced on the average by 18%. Figures (5) through (7) show the difference in ripple voltage with and without the flat bus under generator loaded conditions.

Distortion Spectrum Measurements

DC distortion is the superimposed alternating voltages on the generator's DC output. This distortion was measured from 10 Hz to 500 kHz at generator speeds from 10,000 to 18,000 rpm at 1000 rpm increments at no load, 25%, 50%, and 75% loads. The distortion spectrum was observed on a Norland oscilloscope that converted the generator output waveform into the frequency domain by taking the Fast Fourier Transform of the time domain. At each test condition, the highest amplitude points and the frequencies that they occurred at were recorded. All distortion measurements were taken without the flat bus cable connected in order to assess the worst case distortion. Measurements of distortion with flat bus were not taken due to time and funding constraints. However, from the results of the ripple measurements, it is believed that the flat

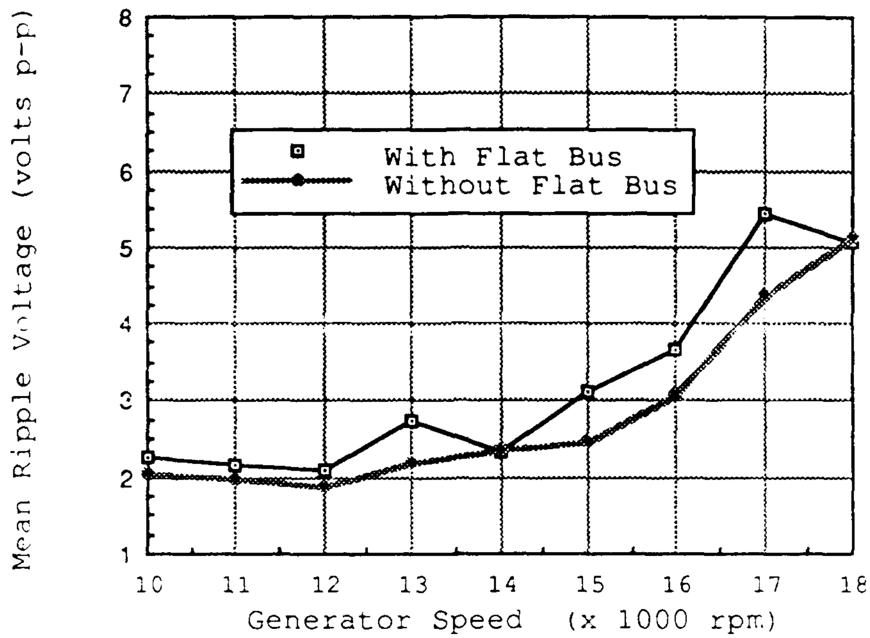


Figure 4. Ripple at No Load

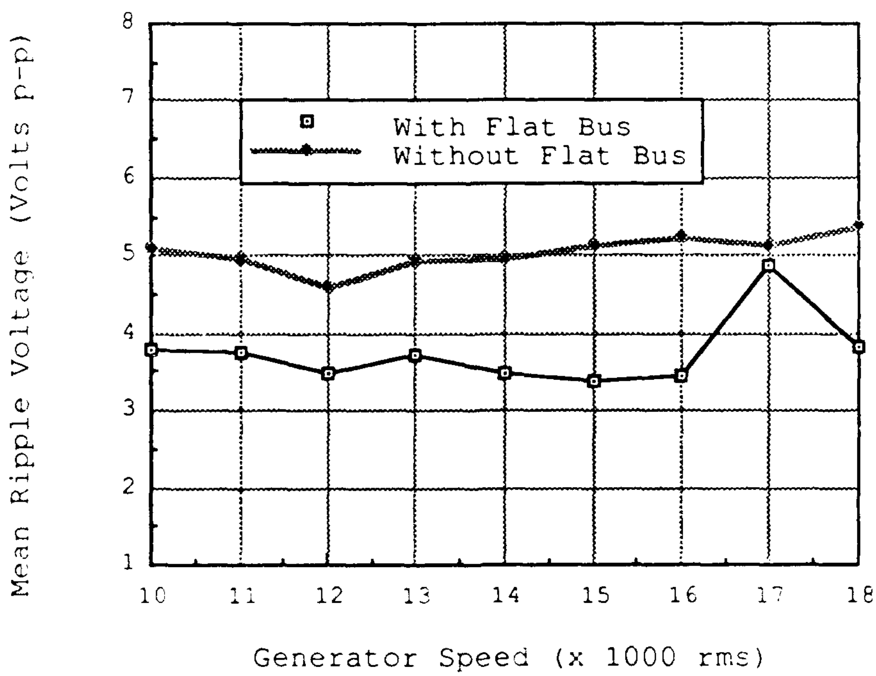


Figure 5. Ripple at 25% Load

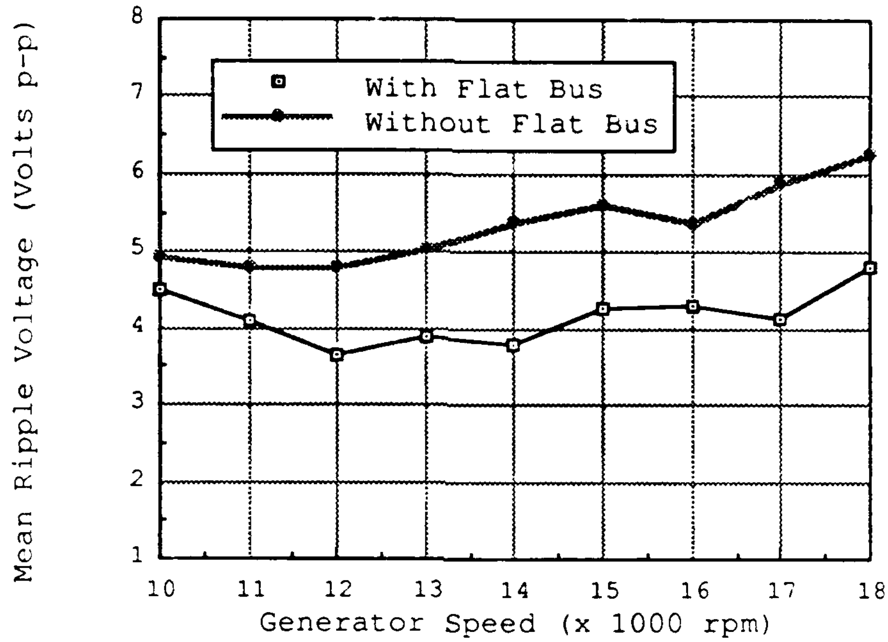


Figure 6. Ripple at 50% Load

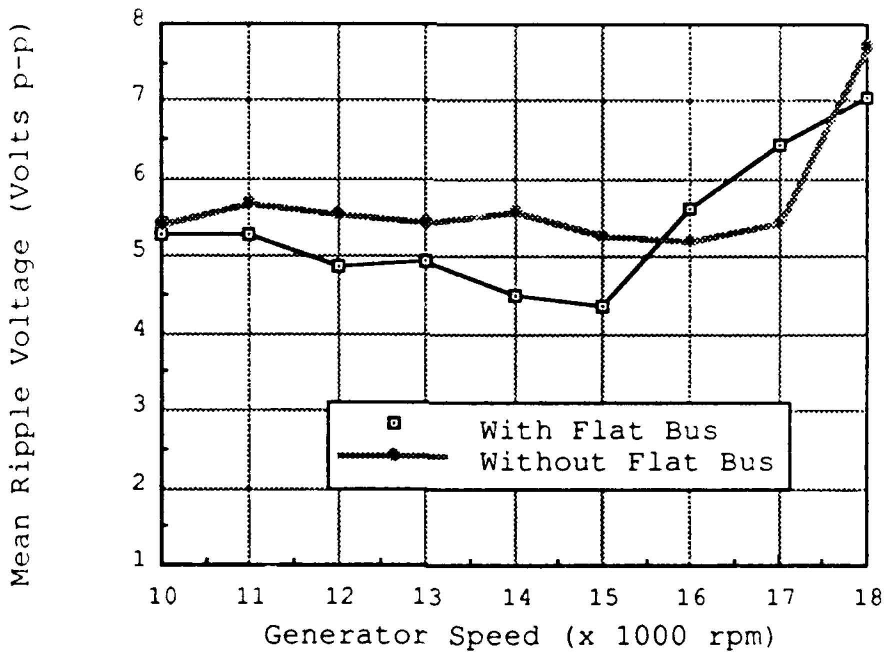


Figure 7. Ripple at 75% Load

cable would suppress distortion. The measured distortion amplitudes were plotted along with the distortion curve from Appendix A for each test condition. These plots are included in Appendix B. At every test condition, the distortion amplitude was well below the limits specified in Appendix A. The distortion factor was calculated for each test condition with the worst case dc distortion. In every case, the distortion factor is well below the recommended limit of 0.010 from Appendix A. Table (1) lists the distortion factor for each condition. The worst distortion factor for each load condition is emphasized in bold print. The overall worst distortion (0.0021) occurred at minimum speed (10,000 rpm) and maximum load (75%).

Table 1. Distortion Factor

Speed (rpm)	No Load	25% Load	50% Load	75% Load
10,000	0.0009	**0.0017**	**0.0019**	**0.0021**
11,000	0.0006	0.0013	0.0010	0.0018
12,000	0.0005	0.0009	0.0010	0.0014
13,000	0.0004	0.0011	0.0010	0.0019
14,000	0.0004	0.0011	0.0014	0.0019
15,000	0.0006	0.0010	0.0013	0.0021
16,000	0.0006	0.0008	0.0011	0.0016
17,000	**0.0011**	0.0010	0.0012	0.0015
18,000	0.0006	0.0008	0.0006	0.0015

Transient Testing

During transient testing, the onset of a transient occurs when a load is applied to or removed from the generator under test. Two parameters were recorded during this testing, recovery time and transient voltage spread. The recovery time is the time from the initial onset of the transient to the time when the generator output voltage returns to steady state (250 - 280 V). In some cases of load switching, the transient is not severe enough to exceed the steady state limits. For these cases, there is no recovery time. The transient voltage spread is the voltage difference between the maximum and minimum voltage that occur during the transient condition. The voltage spread number gives a good indication of the severity of the transient.

Table (2) summarizes data taken during load application tests at different speeds and loads. In general, the transient voltage spread increased as the load and speed increased. On the other hand, speed and load did not have a significant effect on the recovery time. The recovery time was much longer during the application of 25% load at 14,000, 16,000, and 18,000 rpm and during the application of 50% load at 16,000 and 18,000 rpm than during any other load application test condition. The extended recovery time was due to the fact that the transient waveform contained a voltage overshoot that exceeded steady state voltage following the normal undershoot that occurs with load application. This overshoot is probably a result of the GCU's difficulty in regulating at low loads and high speeds. Although the recovery time was longer at the stated conditions, the transient still remained within the envelope of the transient curves in reference (2).

The one case that the transient performance did not meet the requirements of reference (2) occurred during load application of the 75% load. The voltage level dropped below the specified 200 Volt limit to 187.5 Volts. Improved techniques for transient suppression are available today, so this failure is not a

Table 2. Data from Load Application Transients

Load Applied (%)	Generator Speed (rpm)	Recovery Time (ms)	Voltage Spread (volts)
25	10,000	0.5	46.9
25	12,000	0.6	50.8
25	14,000	14.2	62.5
25	16,000	18.0	70.3
25	18,000	19.7	82.0
50	10,000	1.9	54.7
50	12,000	1.9	70.3
50	14,000	3.0	70.3
50	16,000	6.6	78.1
50	18,000	8.9	78.1
75	10,000	4.4	85.9
75	12,000	3.5	85.9
75	14,000	3.3	89.8
75	16,000	3.3	93.8
75	18,000	3.0	89.8

significant problem.

Table (3) summarizes data recorded during load removal at different speeds and loads. Here, the recovery time does seem to depend upon the speed of the generator and the amount of the load being removed. The recovery time is longer for faster speeds and higher loads. The voltage spread generally increased with increasing load, but there was no significant effect of speed on the voltage spread.

The average recovery time for load removal is 18.5 ms while the average recovery time for load application is only 6 ms. In general, it takes about 3 times longer to recover from a load removal than from a load application at the same percentage load and the same generator speed. On the other hand, the average

transient voltage spread for load removal (17 Volts) is less than that for load application (74 Volts). Figure (8) is a typical comparison of the transients incurred by load removal and load application.

Table 3. Data from Load Removal Transients

Load Removed (%)	Generator Speed (rpm)	Recovery Time (ms)	Voltage Spread (volts)
25	10,000	6.6	14.8
25	12,000	8.2	12.8
25	14,000	None	9.2
25	16,000	15.4	10.9
25	18,000	16.2	12.3
50	10,000	9.4	13.9
50	12,000	10.4	11.1
50	14,000	16.0	15.0
50	16,000	18.6	12.2
50	18,000	18.0	14.8
75	10,000	20.0	27.7
75	12,000	22.8	26.6
75	14,000	29.0	25.8
75	16,000	33.0	26.7
75	18,000	35.8	26.6

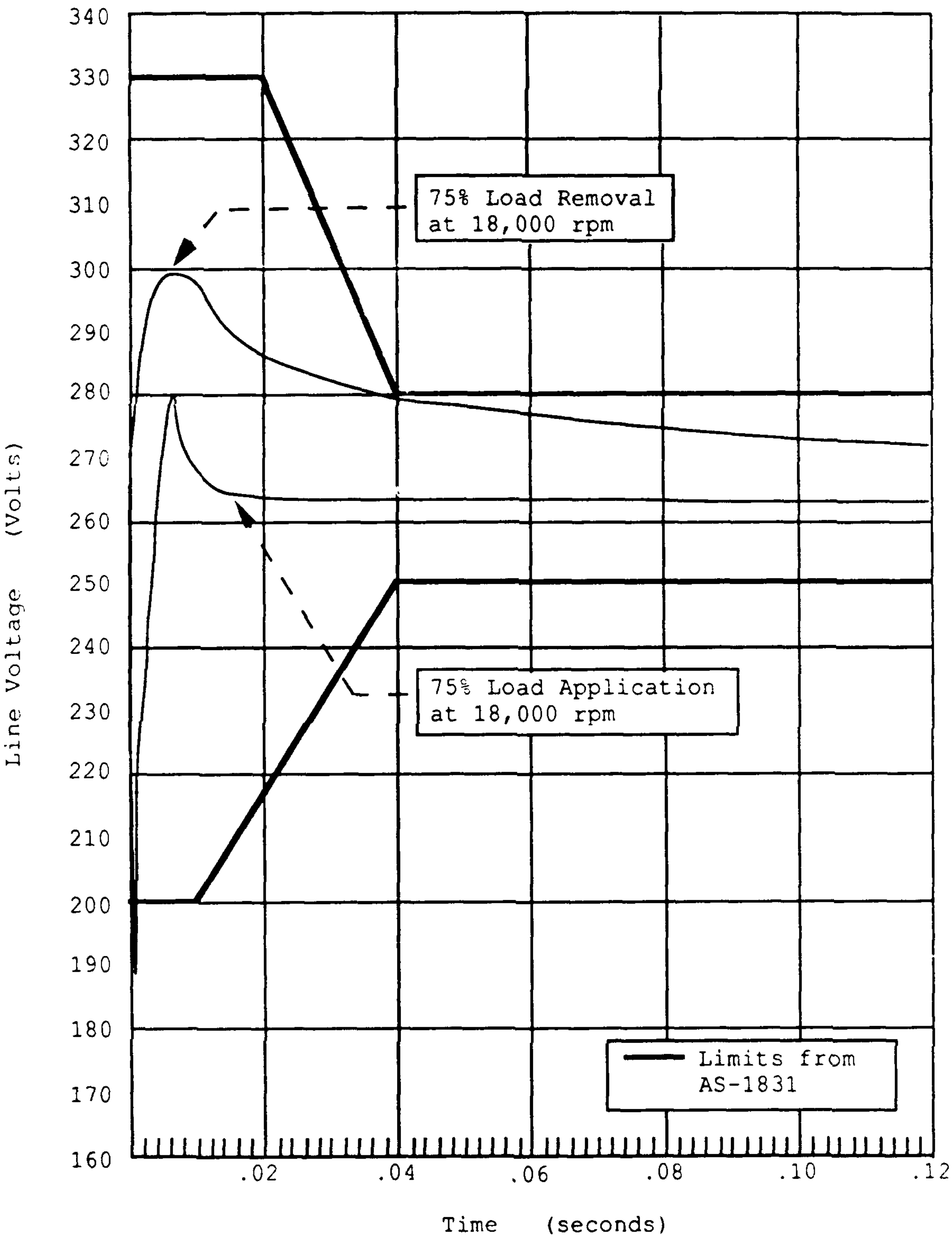


Figure 8. Example Plot of Transient Line Voltages

In order to decrease the severity of voltage transients, a method of stepped load application and removal has been investigated. The load was stepped up from no load to 18% to 27% to 56%. Transient voltage spreads and recovery time were recorded for each step up and also for a direct turn-on from no load to 56% in Table (4). Table (5) provides similar data for load removal. The voltage spreads for stepped loading were much less severe than for direct loading. Also the recovery times were shorter or even non-existent for stepped loading.

Since the transients from incremental loading were much smaller than the transients from direct loading, they had to be measured using the A.C. mode of the oscilloscope. The A.C. mode of the scope could not capture transients from direct loading greater than 56% load. So, rather than switch to D.C. mode to measure the larger transients and risking inconsistent measurements, the incremental loading testing was limited to 56% loading. The direct loading transients were measured using the D.C. mode of the oscilloscope. For this reason Tables (2) & (3) should not be compared to Tables (4) & (5).

Table 4. Data from Incremental Load Application

Initial Load (%)	Load Applied (%)	Generator Speed (rpm)	Recovery Time (ms)	Transient Voltage Spread (Volts)
0	18	10,000	0.45	35.9
18	27	10,000	0.90	11.7
27	56	10,000	0.40	28.1
0	**56**	**10,000**	**3.10**	**43.8**
0	18	12,000	0.45	41.8
18	27	12,000	None	11.7
27	56	12,000	0.40	28.9
0	**56**	**12,000**	**2.75**	**58.6**
0	18	14,000	0.45	50.8
18	27	14,000	None	13.3
27	56	14,000	0.40	28.1
0	**56**	**14,000**	**2.35**	**65.6**
0	18	16,000	0.55	57.8
18	27	16,000	None	28.9
27	56	16,000	0.40	29.7
0	**56**	**16,000**	**2.15**	**69.5**
0	18	18,000	0.45	63.3
18	27	18,000	None	16.4
27	56	18,000	0.35	31.3
0	**56**	**18,000**	**2.05**	**69.5**

Conclusion

Every test performed on the Lucas generator exceeded expectations. Not only did the generator perform up to the standards specified in the type specification that it was designed to, but it also met the tighter requirements of MIL-STD-704D, Appendix A, and AS-1831. The only exception was the transient drop below 200 Volts during the 75% load application.

The general operating performance of the generator was established by the measurements of line voltage and field current. The line voltage was properly regulated and well within the MIL-STD-704D limits for steady state operation during all speeds and load conditions. The ripple measurements yielded an average ripple of 4.7 V p-p which is considerably below the limit of 12 V p-p stated in MIL-STD-704D, and it is also below the 9.6 V p-p limit called out in Appendix A. It has also been shown that the use of flat bus cable reduces ripple. Further investigation into this area is recommended. The results of the distortion measurements clearly indicate that a 270 VDC generator can meet the criteria outlined by the distortion spectrum in Appendix A.

The transient measurements were the only limiting factor of the 270 VDC generator. In most cases, the generator performed satisfactorily; however, under large load applications, the generator had difficulty suppressing the transient as required by AS-1831. Transient suppression circuits are available today to combat this problem. Another alternative is stepped loading which was proven in this paper to be an effective means of reducing transient severity.

Based on this generator, which is over ten years behind today's state-of-the-art, it can be concluded that no significant problems should be encountered by generator vendors in their efforts to meet the new 270 VDC requirements set forth in MIL-STD-704E.

Table 5. Data from Incremental Load Removal

Initial Load (%)	Load Applied (%)	Generator Speed (rpm)	Recovery Time (ms)	Transient Voltage Spread (Volts)
18	0	10,000	4.8	13.7
27	18	10,000	None	6.7
56	27	10,000	None	10.0
56	**0**	**10,000**	**11.4**	**17.8**
18	0	12,000	310.2	11.2
27	18	12,000	None	9.8
56	27	12,000	None	10.1
56	**0**	**12,000**	**20.0**	**16.1**
18	0	14,000	None	7.5
27	18	14,000	None	5.6
56	27	14,000	None	9.1
56	**0**	**14,000**	**17.6**	**16.2**
18	0	16,000	None	8.0
27	18	16,000	None	5.6
56	27	16,000	None	9.2
56	**0**	**16,000**	**28.2**	**13.4**
18	0	18,000	8.2	10.8
27	18	18,000	None	4.4
56	27	18,000	6.6	10.9
56	**0**	**18,000**	**26.4**	**18.3**

REFERENCES

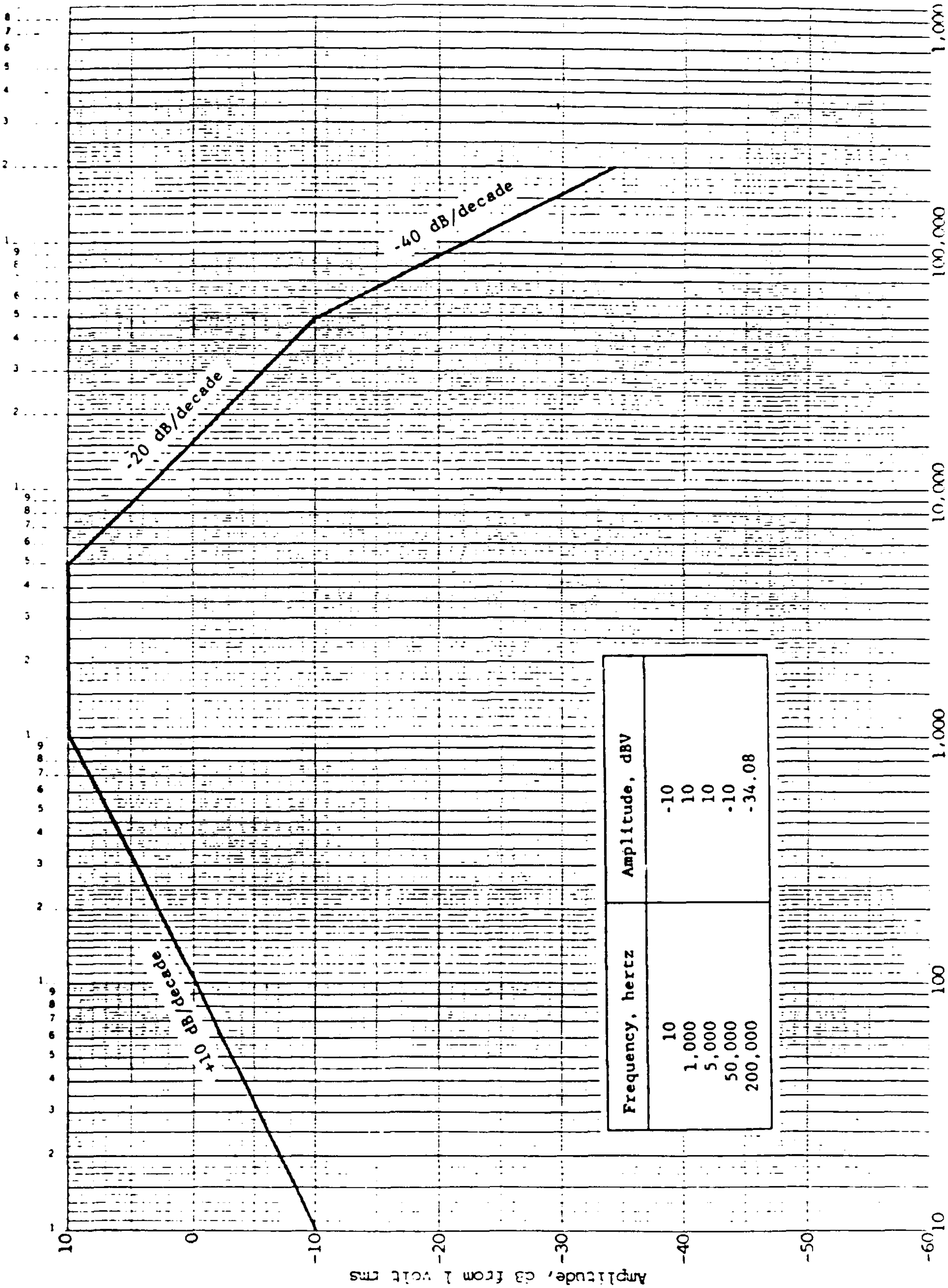
(1) MIL-STD-704D, Aircraft Electric Power Characteristics, 30 September 1980.

(2) AS-1831, Characteristics and Utilization of Aircraft High Voltage Direct Current Electric Power, April 1986.

(3) NADC-60-TS-7803, Generator System, 270 Volts Direct Current, Oil Cooled, Aircraft, General Specification for, 5 January 1978.

Appendix A

Excerpts from White Paper by Mr. Eric Speck



Frequency, hertz	Amplitude, dBV
10	-10
1,000	10
5,000	10
50,000	-10
200,000	-34.08

Figure A-1. Distortion Spectrum of 270 Volt DC voltage (Recommended)

Table A-1. Recommended ripple amplitude, distortion factor and distortion spectrum for MIL-STD-704.

	28 Volt DC	270 Volt DC
Ripple amplitude Distortion factor Distortion spectrum	1.5 volts .035 see below and Fig. 9a	6.0 volts .015 see below and Fig. 9b
at 10 hertz	-20 dBVrms	-10 dBVrms
10 - 1,000 hertz	+10 dB/decade slope	+10 dB/decade slope
1,000 - 5,000	0 dBVrms	+10 dBVrms
5,000 - 50,000	-20 dB/decade slope	-20 dB/decade slope
at 50,000 hertz	-20 dBVrms	-10 dBVrms
50,000 - 200,000	-40 dB/decade slope	-40 dB/decade slope
at 200,000 hertz	-44.08 dBVrms	-34.08 dBVrms

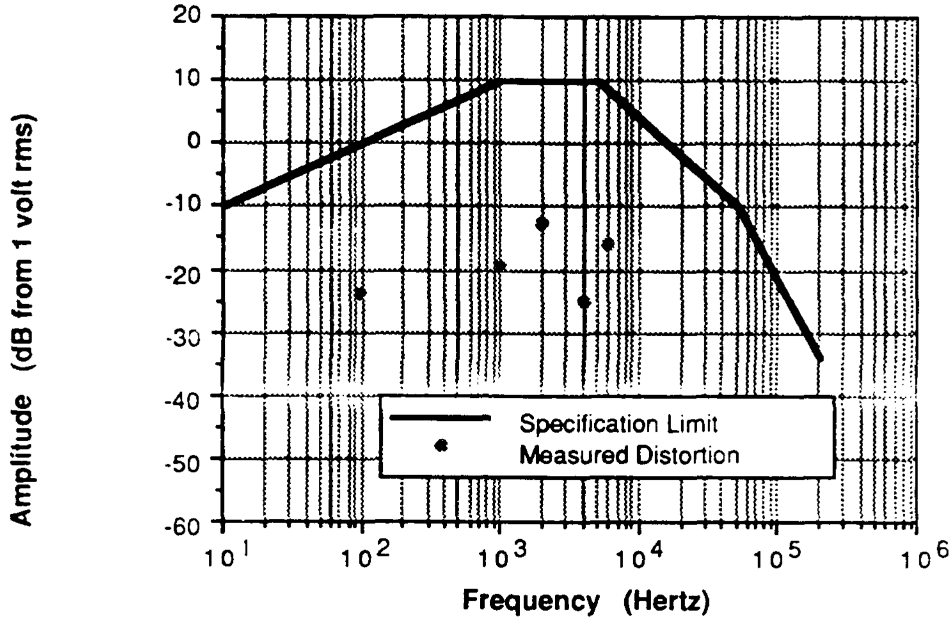
Table A-2 Recommended ripple amplitude, distortion factor and distortion spectrum for dc generator and converter specifications.

	28 Volt DC	270 Volt DC
Ripple amplitude	1.2 volts	4.8 volts
Distortion factor	.025	.010
Distortion spectrum	same as MIL-STD-704	same as MIL-STD-704

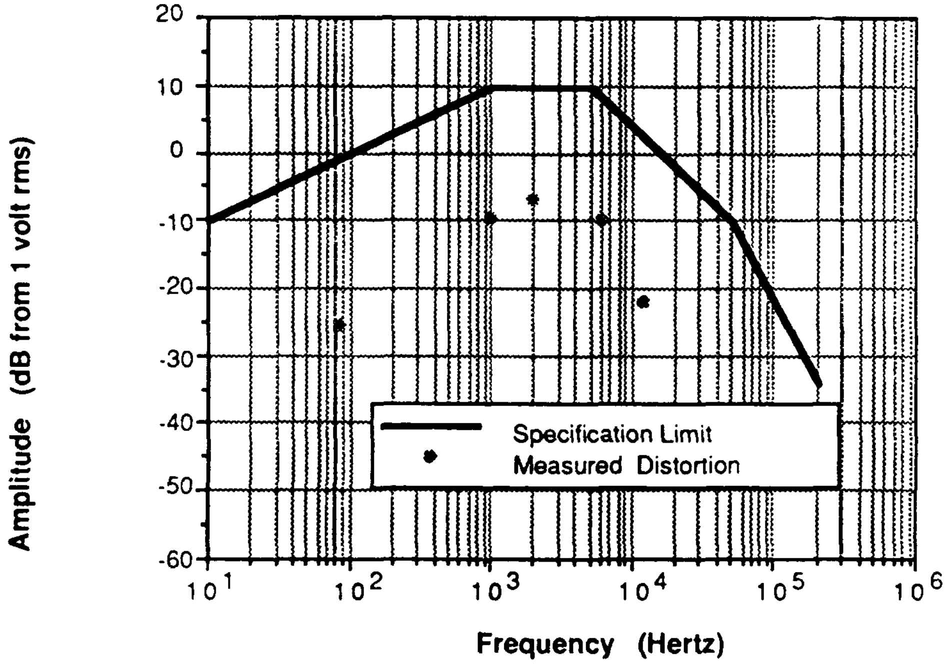
Appendix B

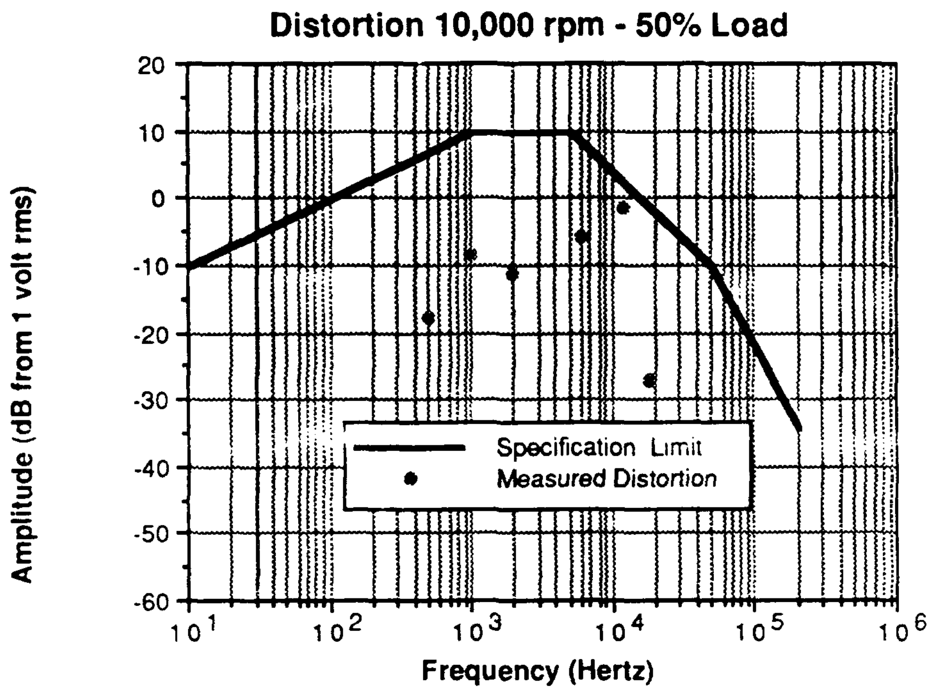
Distortion Spectrum Graphs

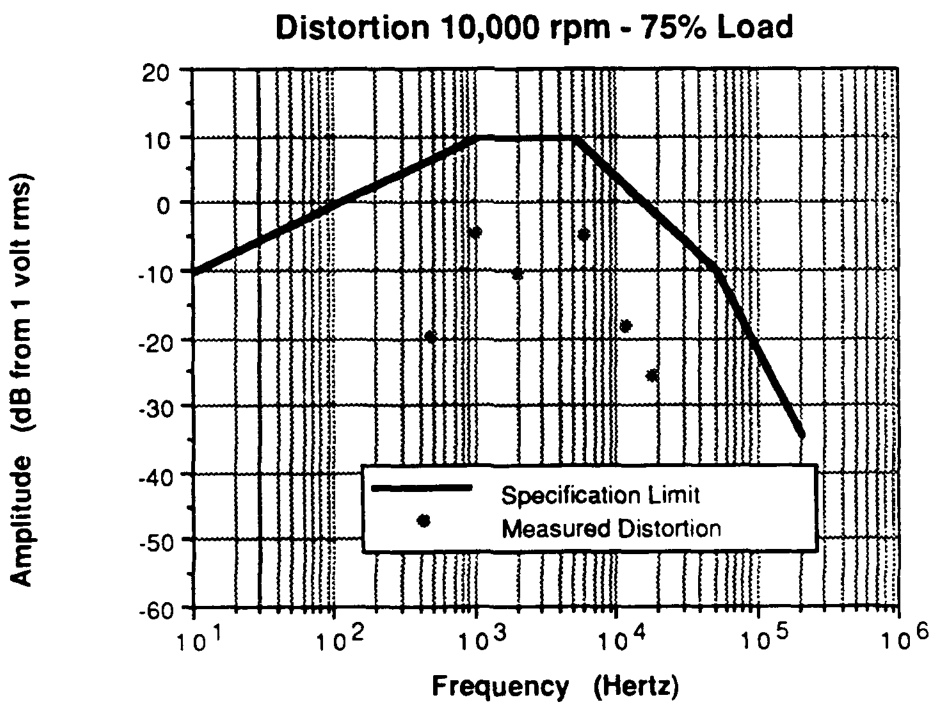
Distortion 10,000 rpm - No Load

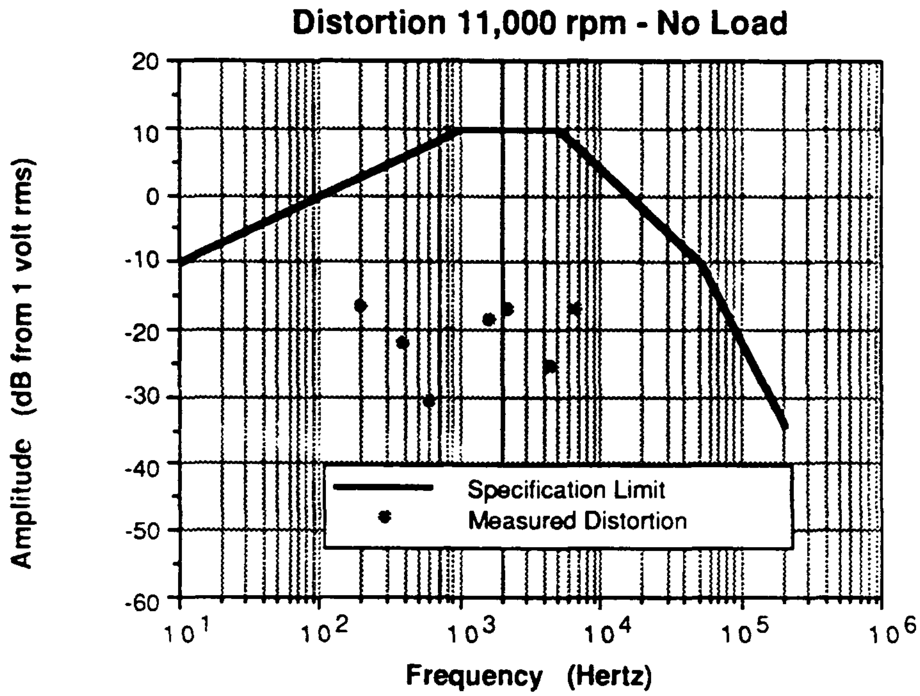


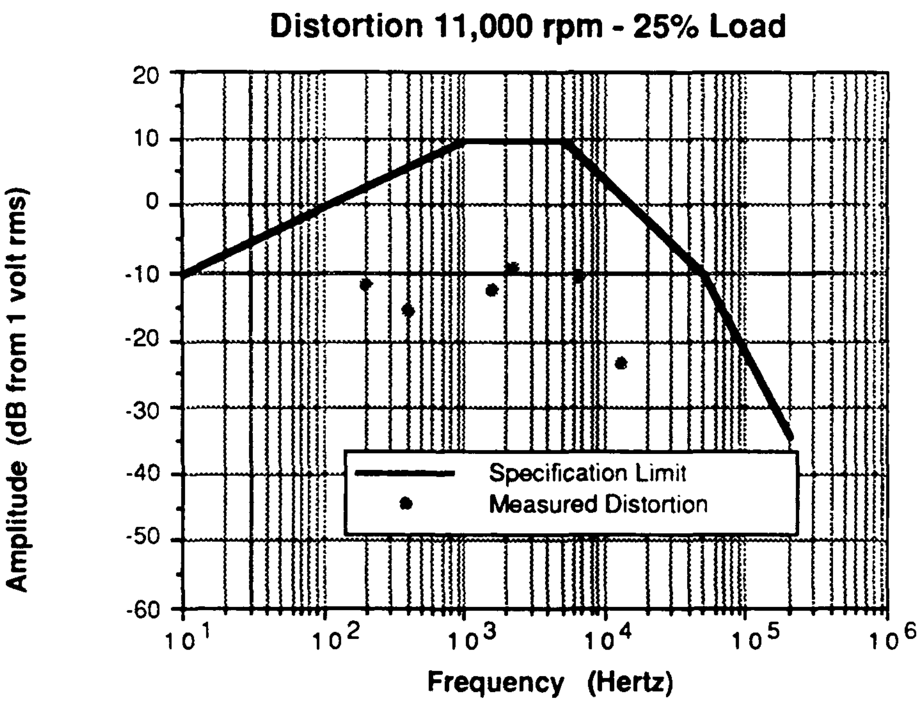
Distortion 10,000 rpm - 25% Load

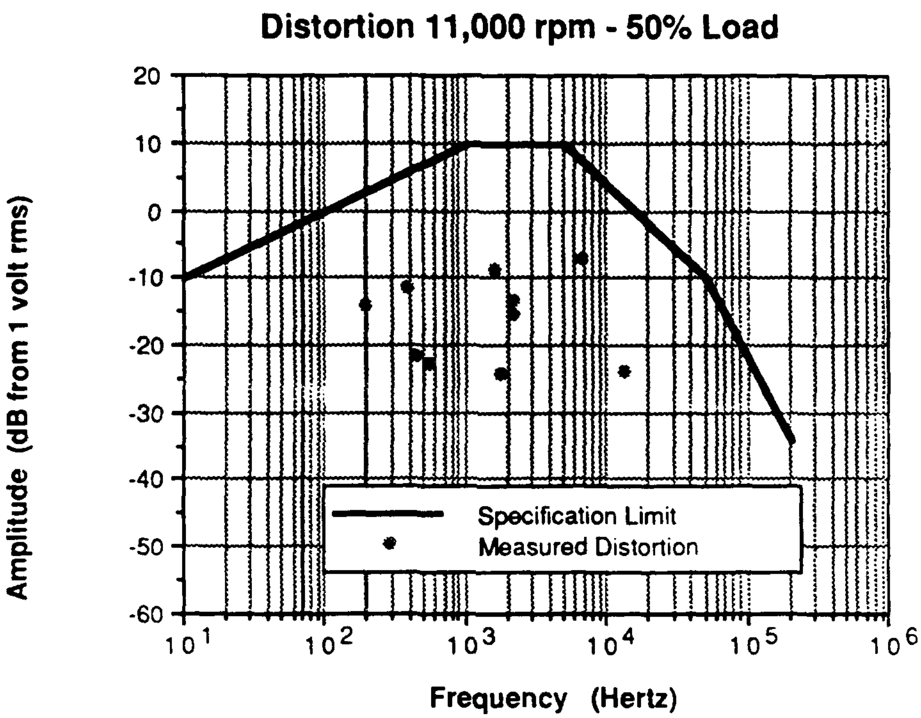


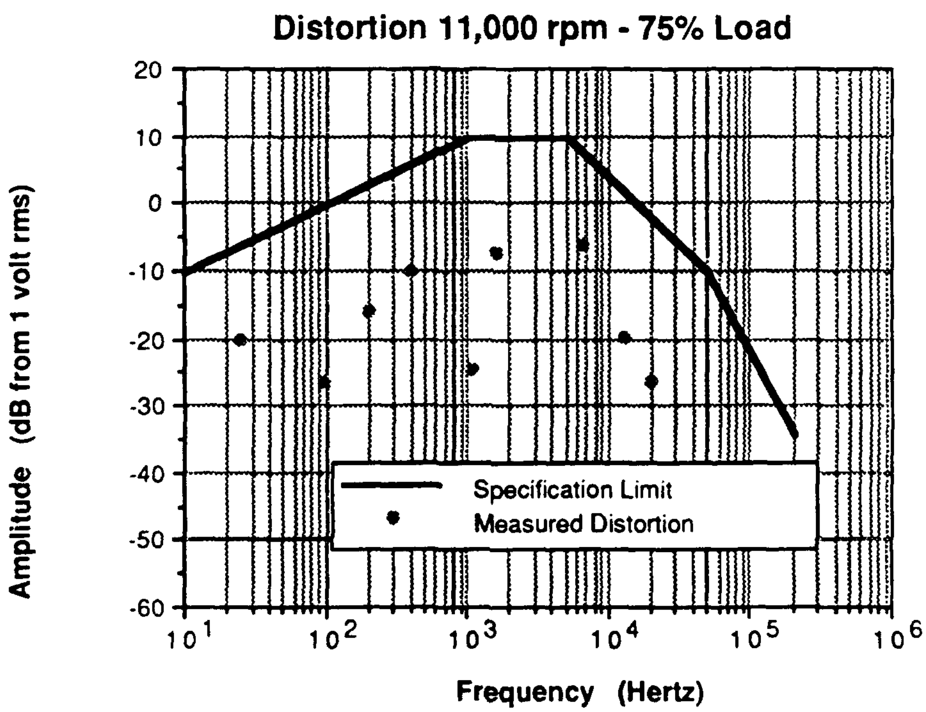

Distortion 10,000 rpm - 50% Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion

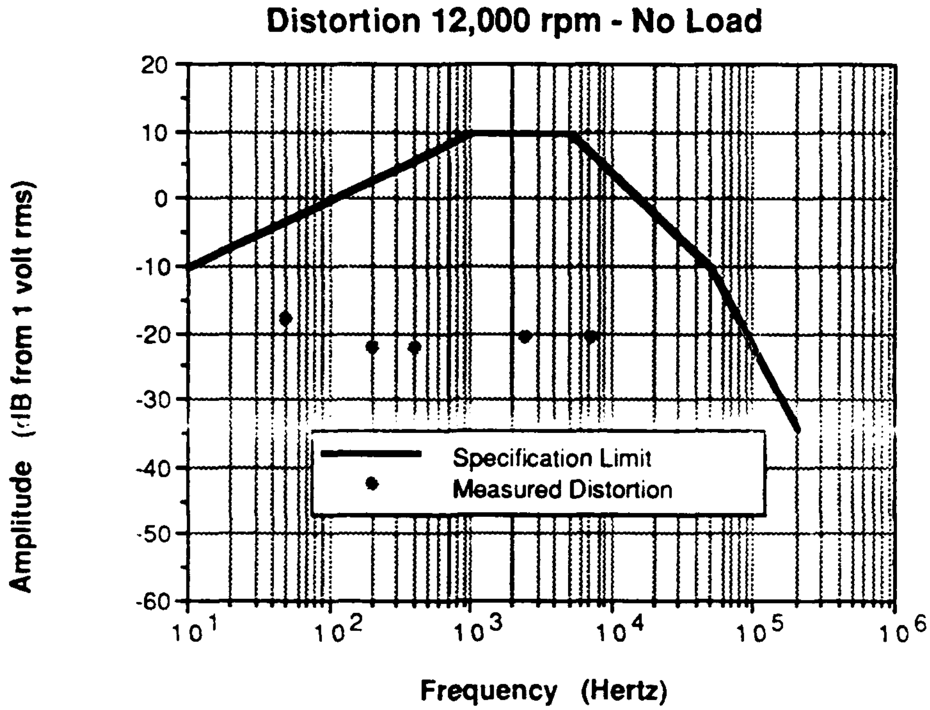

Distortion 10,000 rpm - 75% Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion

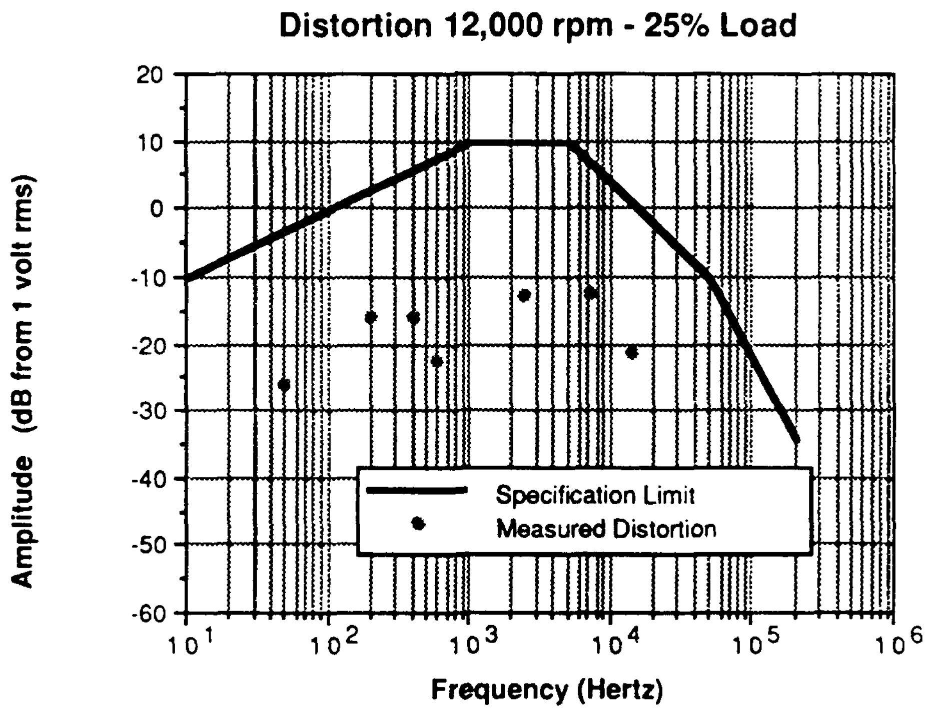

Distortion 11,000 rpm - No Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)


Distortion 11,000 rpm - 25% Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

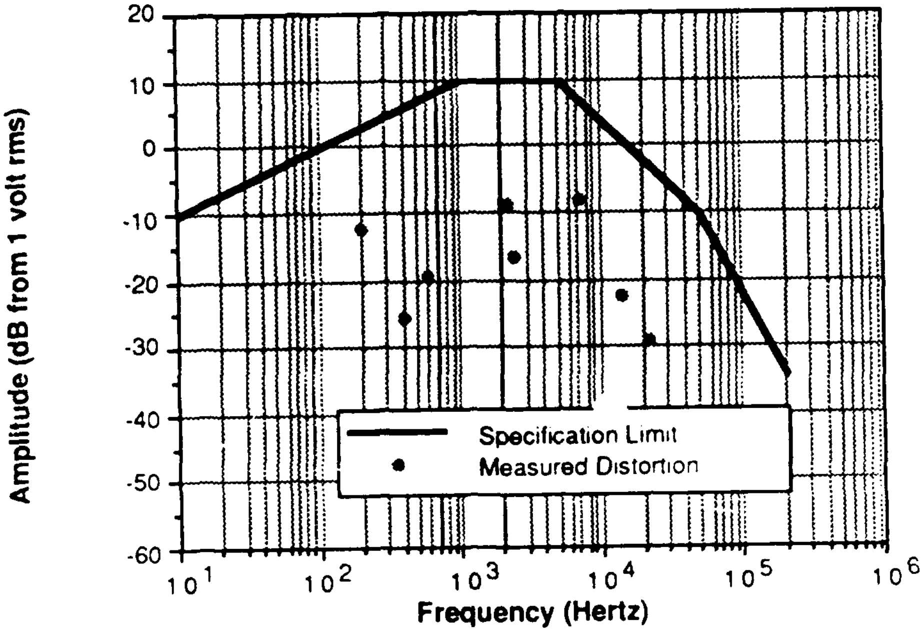

Distortion 11,000 rpm - 50% Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)


Distortion 11,000 rpm - 75% Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

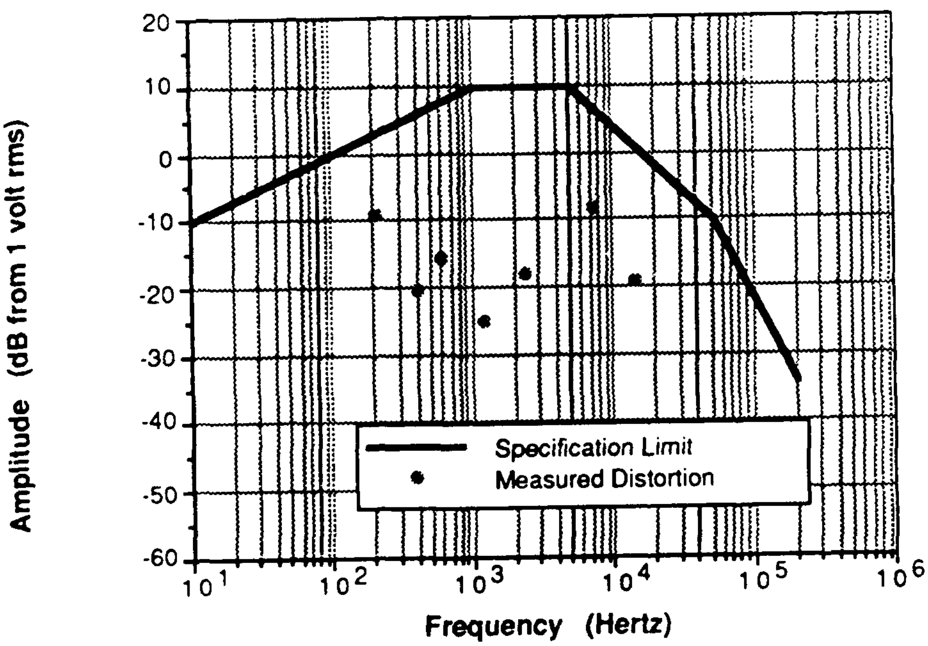

Distortion 12,000 rpm - No Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

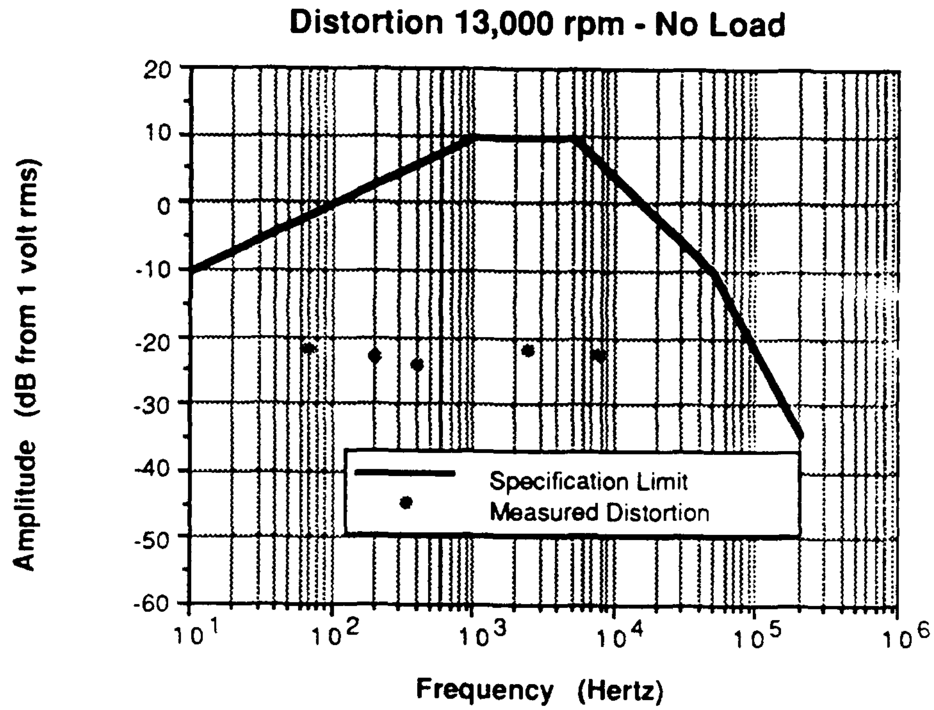

Distortion 12,000 rpm - 25% Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

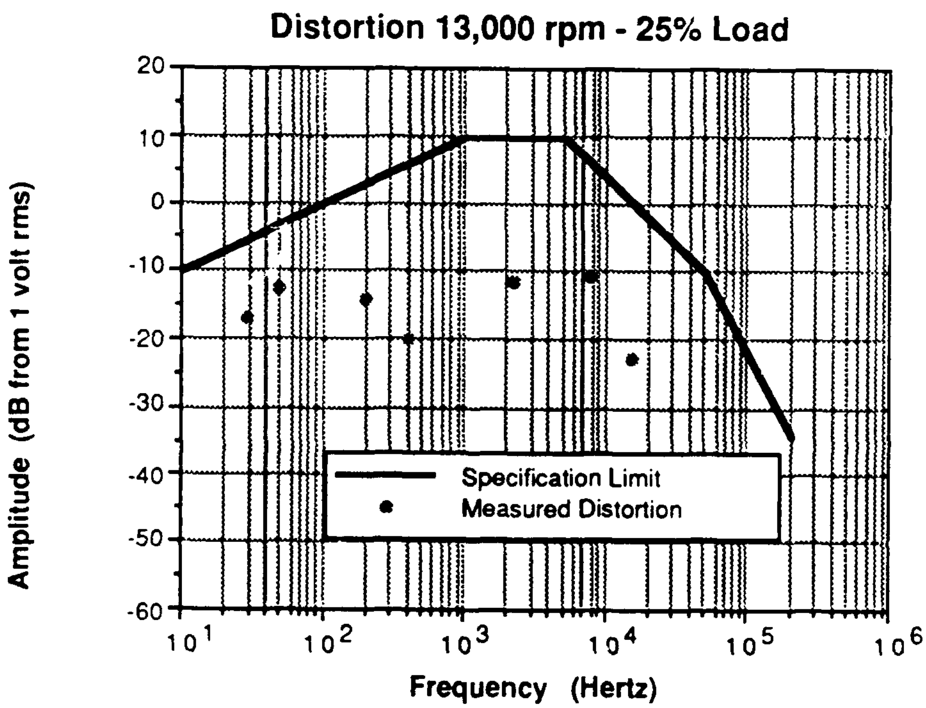
Distortion 12,000 rpm - 50% Load

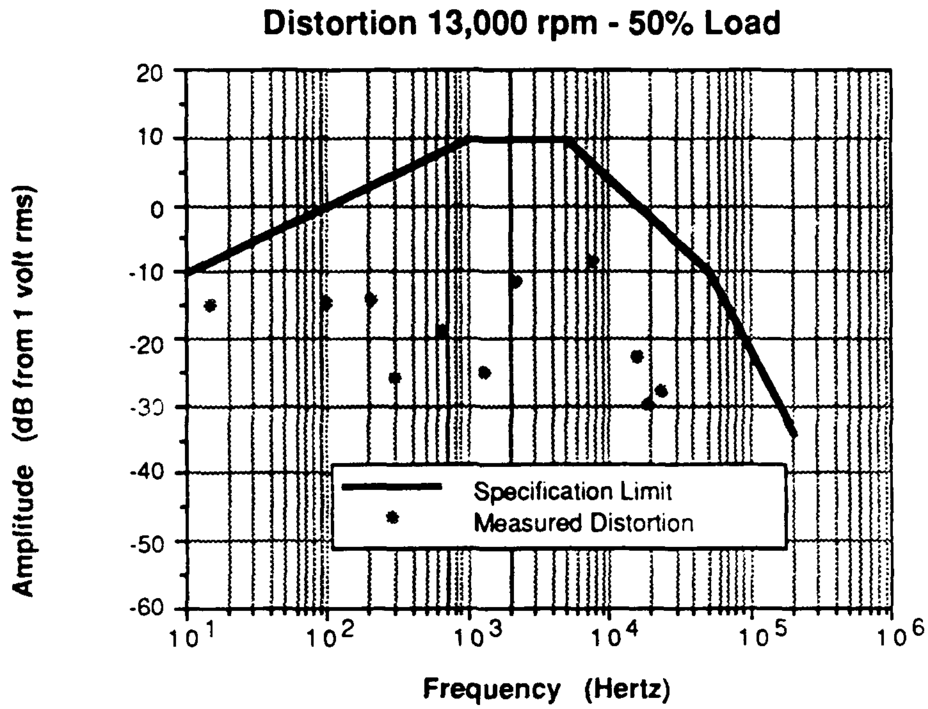


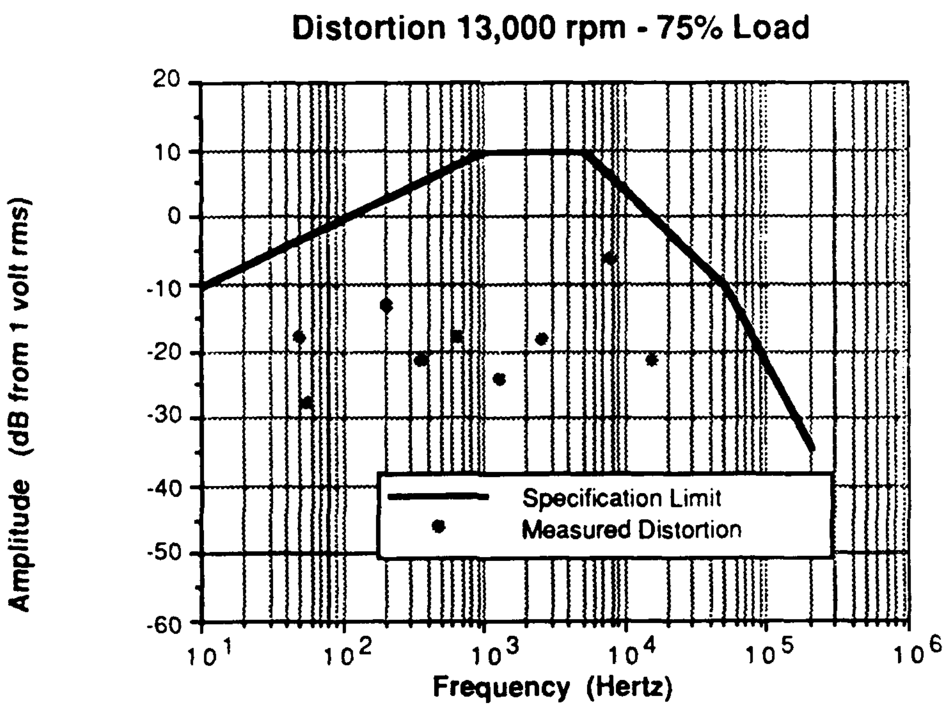
Distortion 12,000 rpm - 75% Load



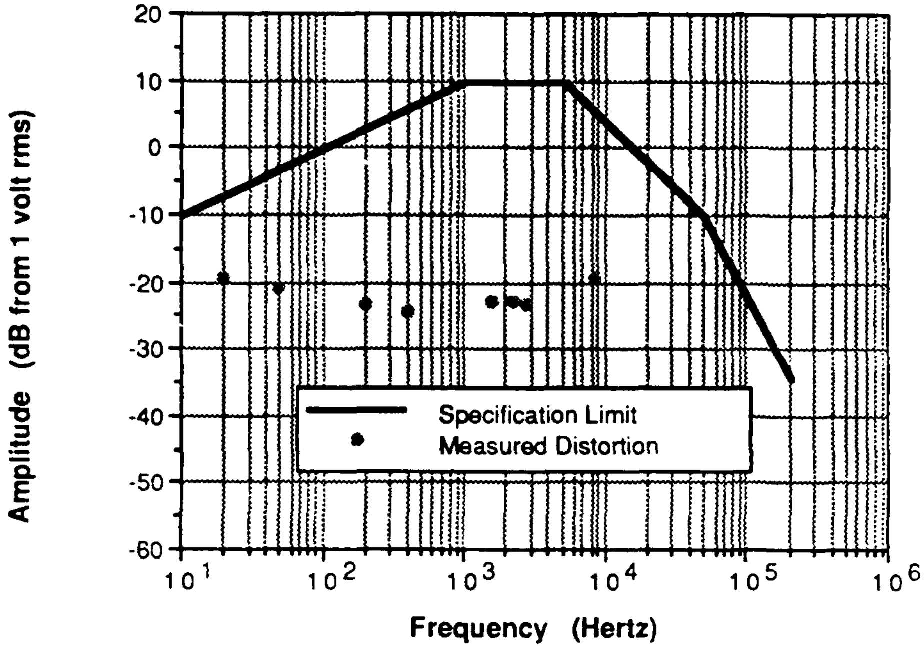

Distortion 13,000 rpm - No Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion


Distortion 13,000 rpm - 25% Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion

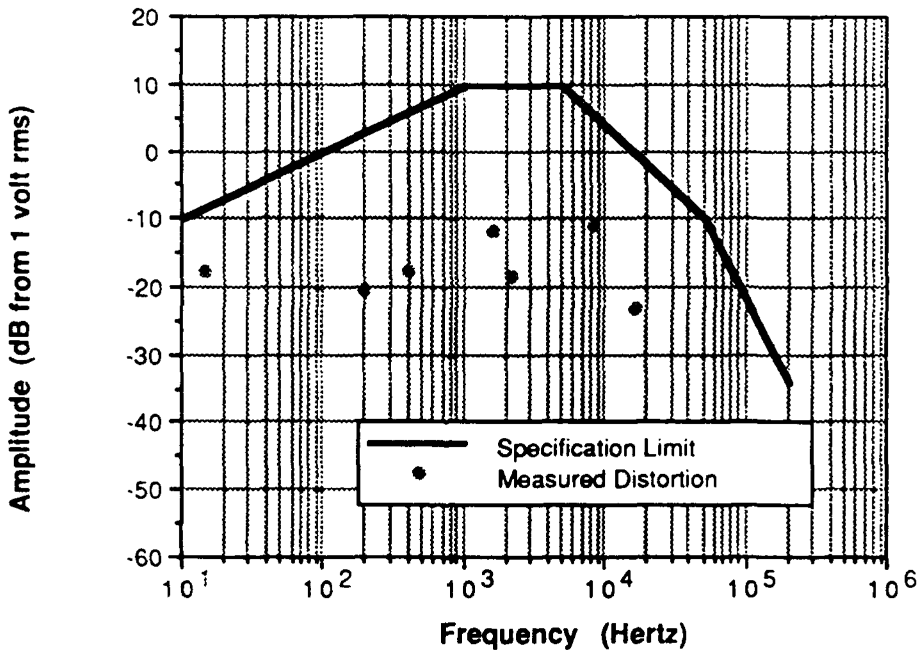

Distortion 13,000 rpm - 50% Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)


Distortion 13,000 rpm - 75% Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

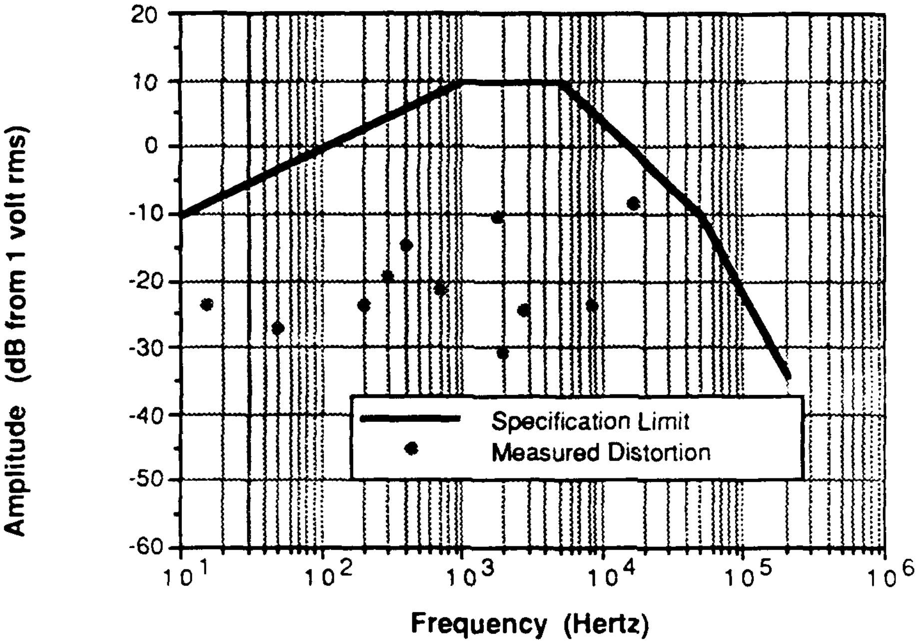
Distortion 14,000 rpm - No Load



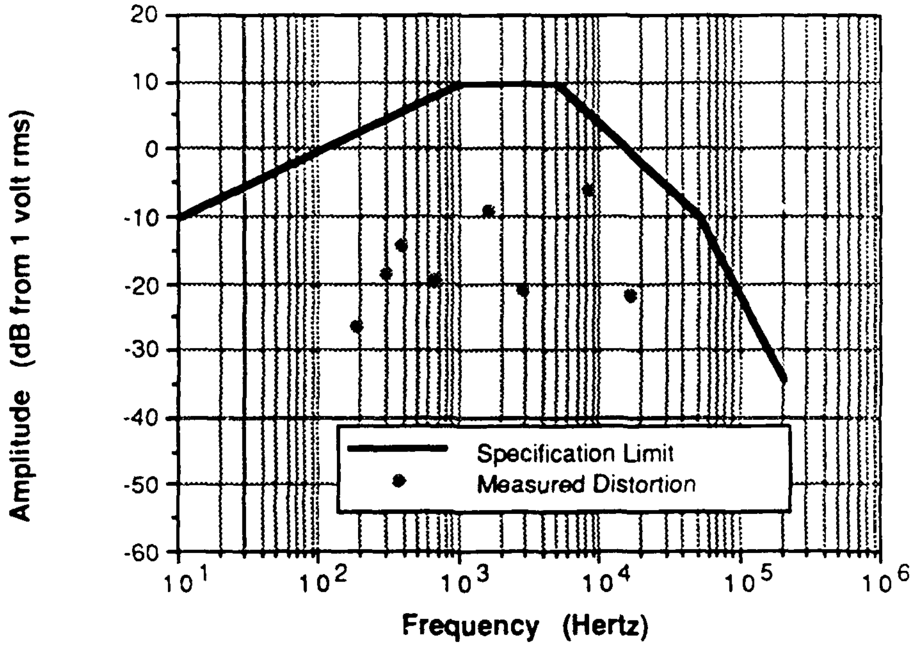
Distortion 14,000 rpm - 25% Load

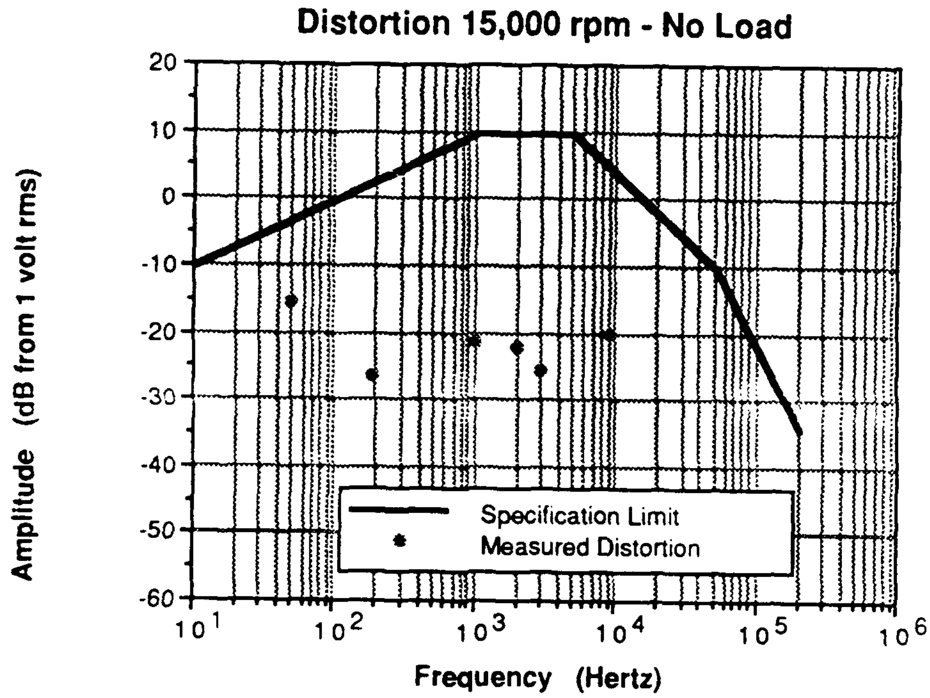


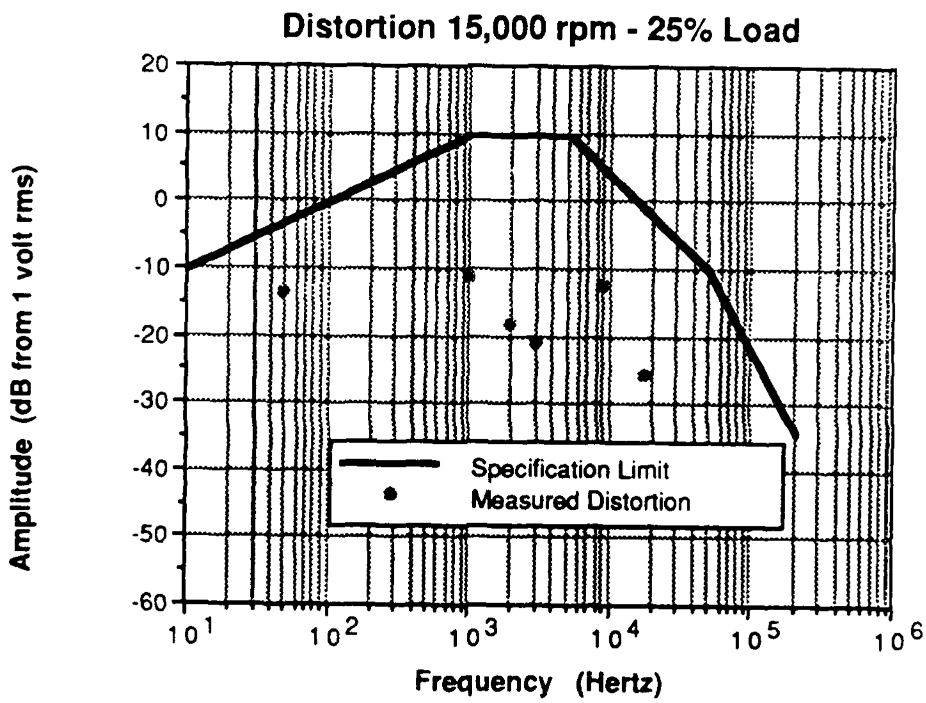
Distortion 14,000 rpm - 50% Load



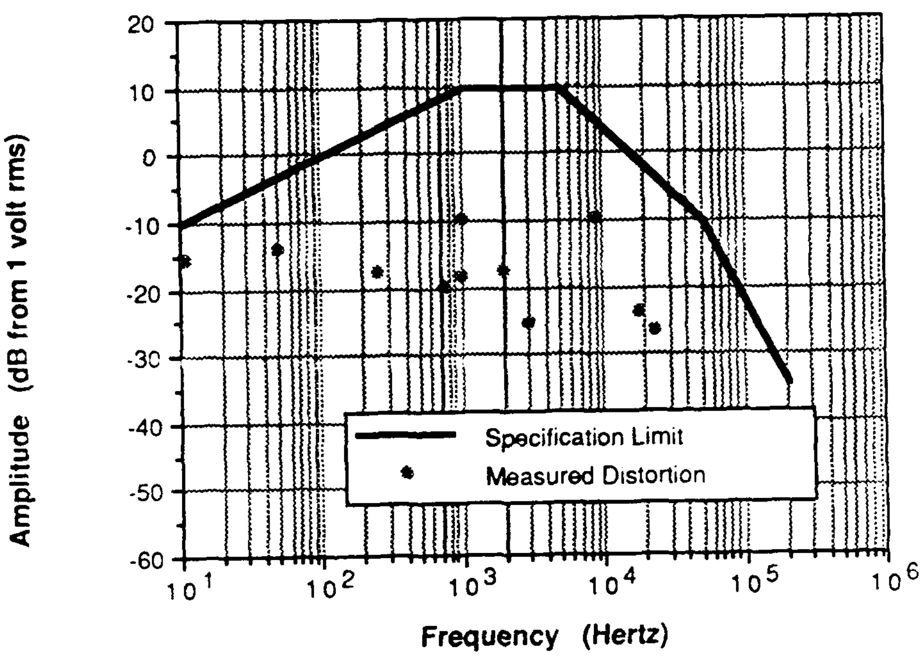
Distortion 14,000 rpm - 75% Load



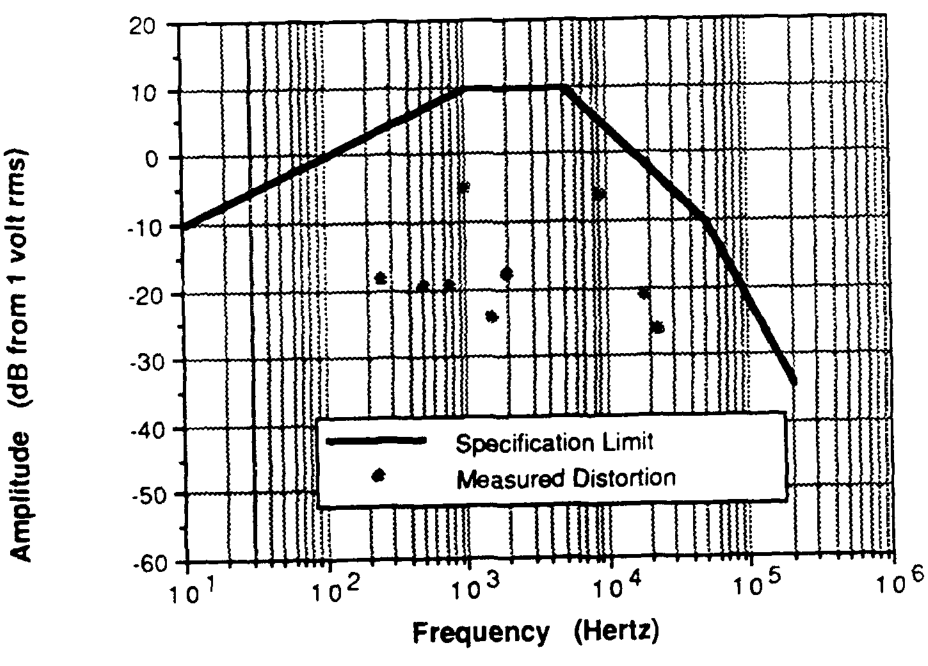

Distortion 15,000 rpm - No Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion

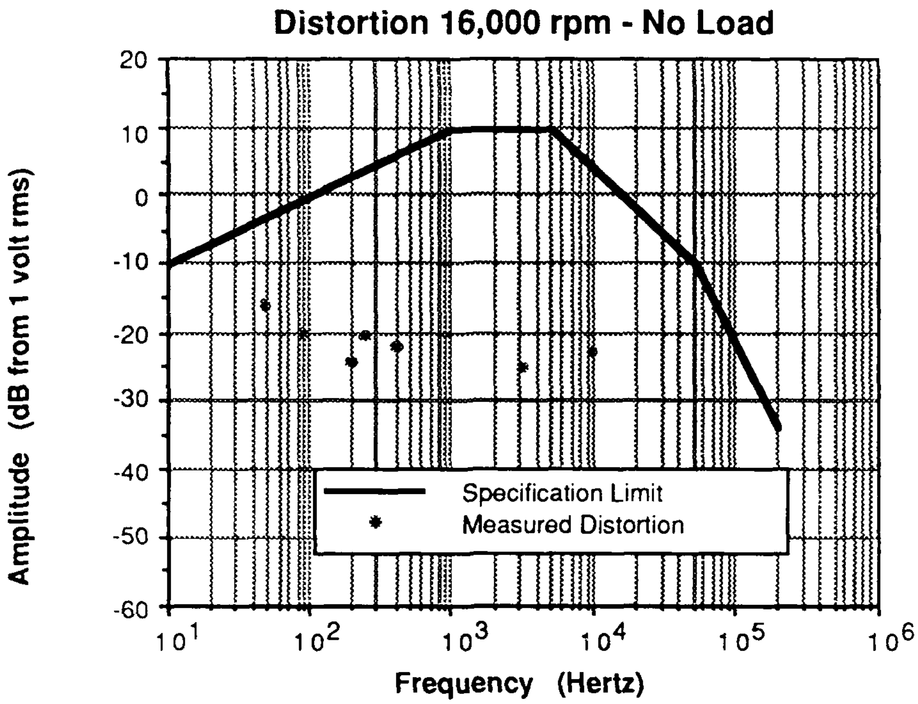

Distortion 15,000 rpm - 25% Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion

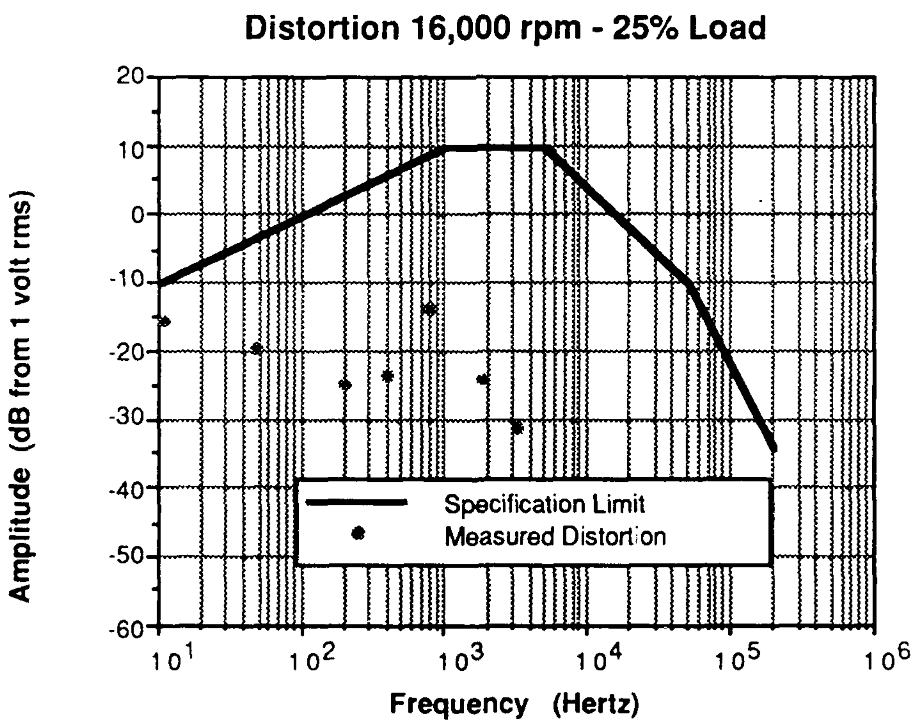
Distortion 15,000 rpm - 50% Load



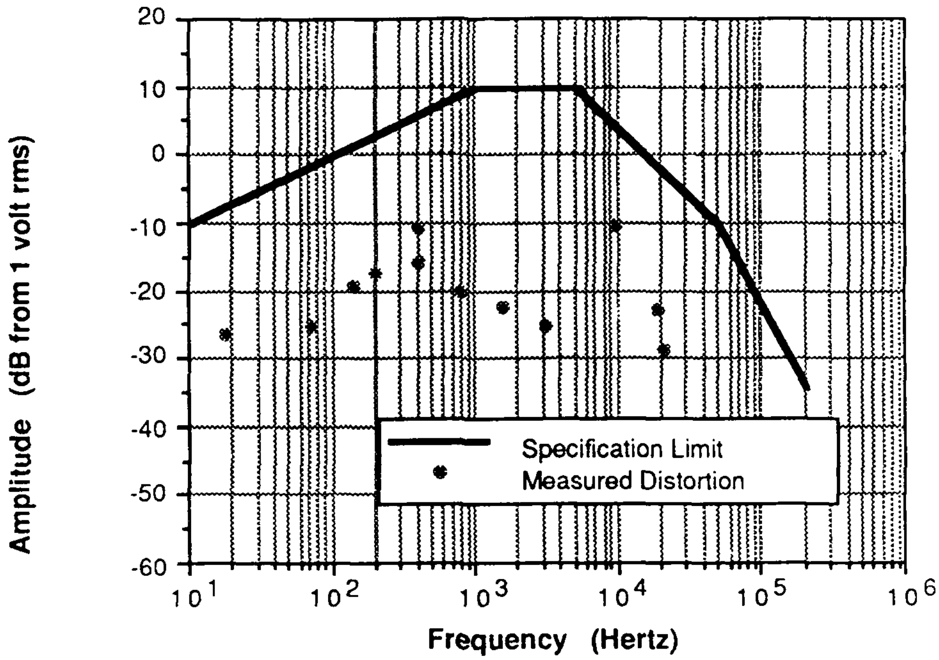
Distortion 15,000 rpm - 75% Load



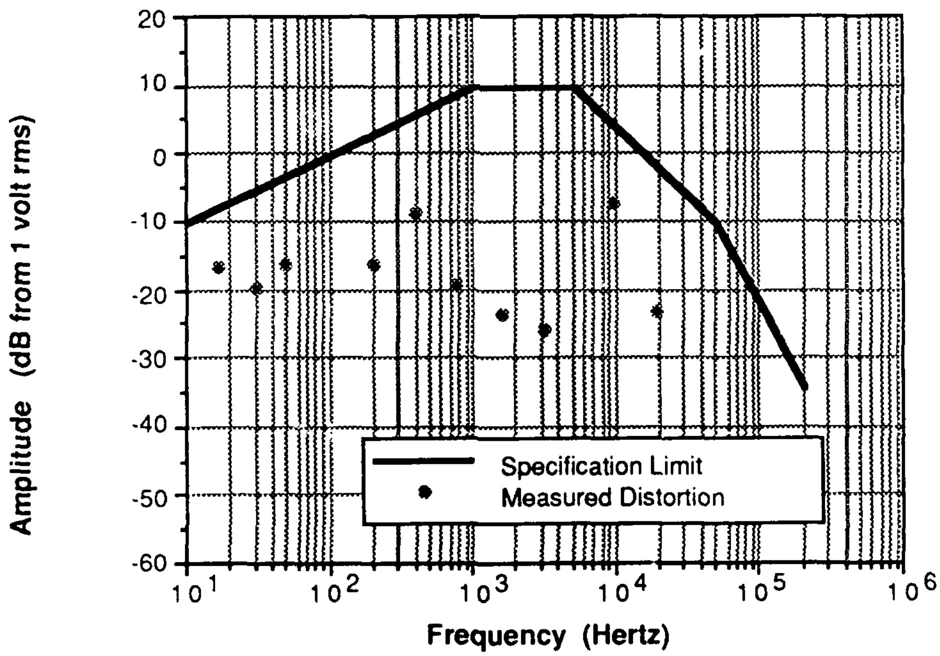

Distortion 16,000 rpm - No Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion

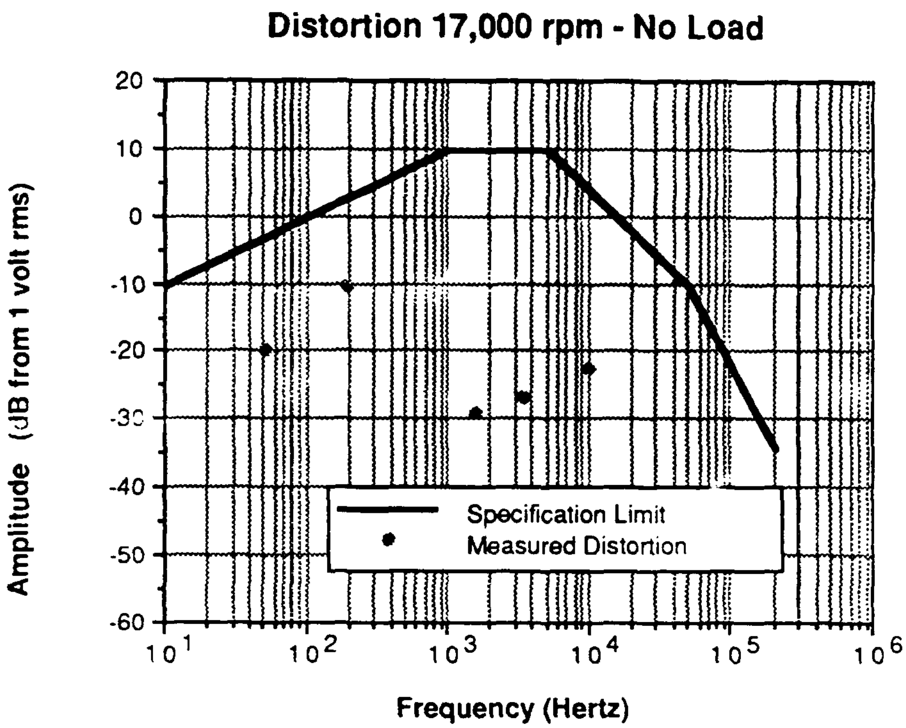

Distortion 16,000 rpm - 25% Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)
Specification Limit
Measured Distortion

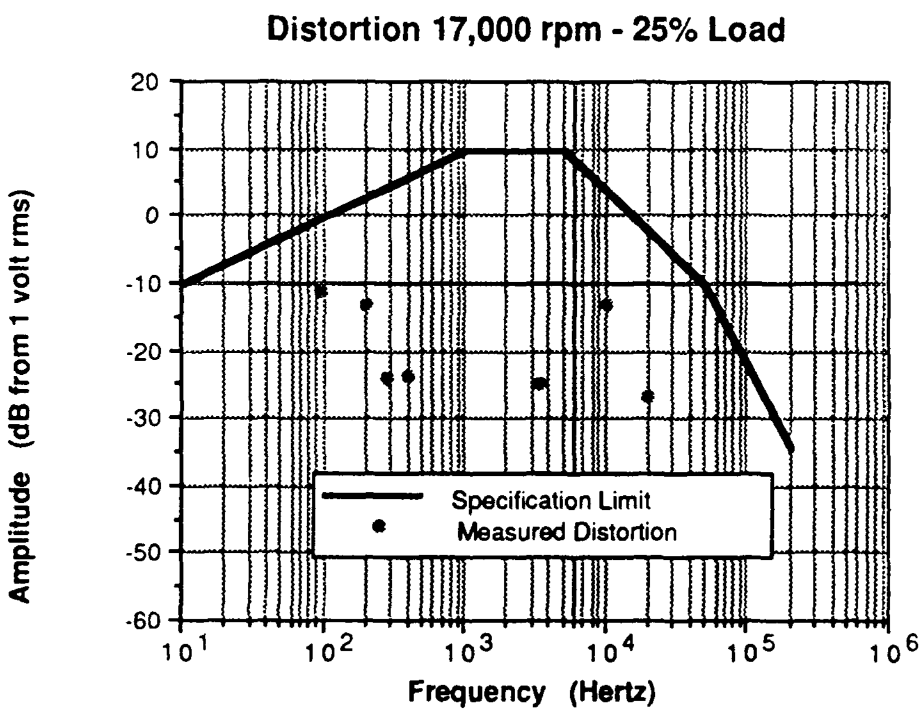
Distortion 16,000 rpm - 50% Load



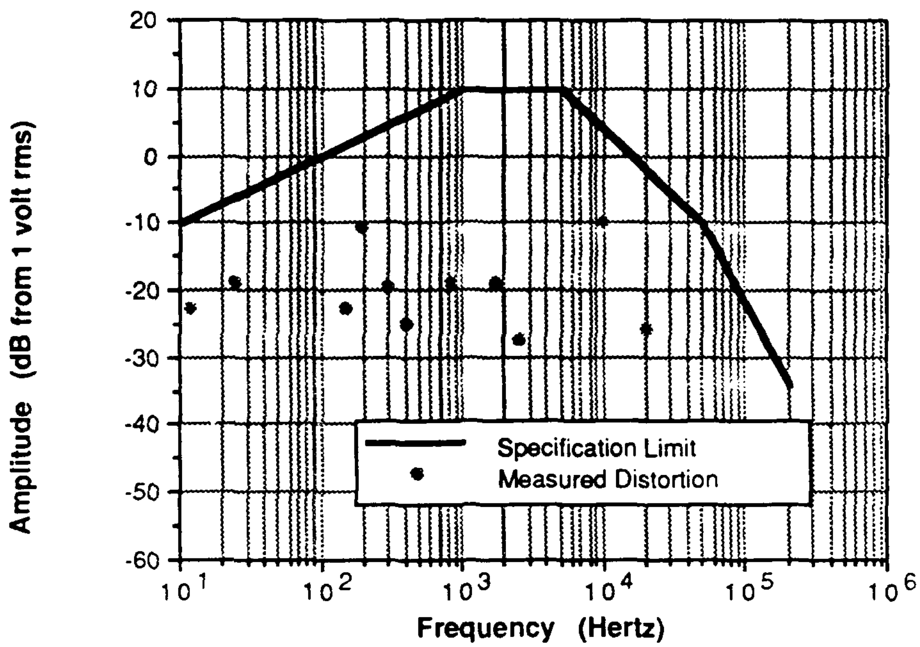
Distortion 16,000 rpm - 75% Load



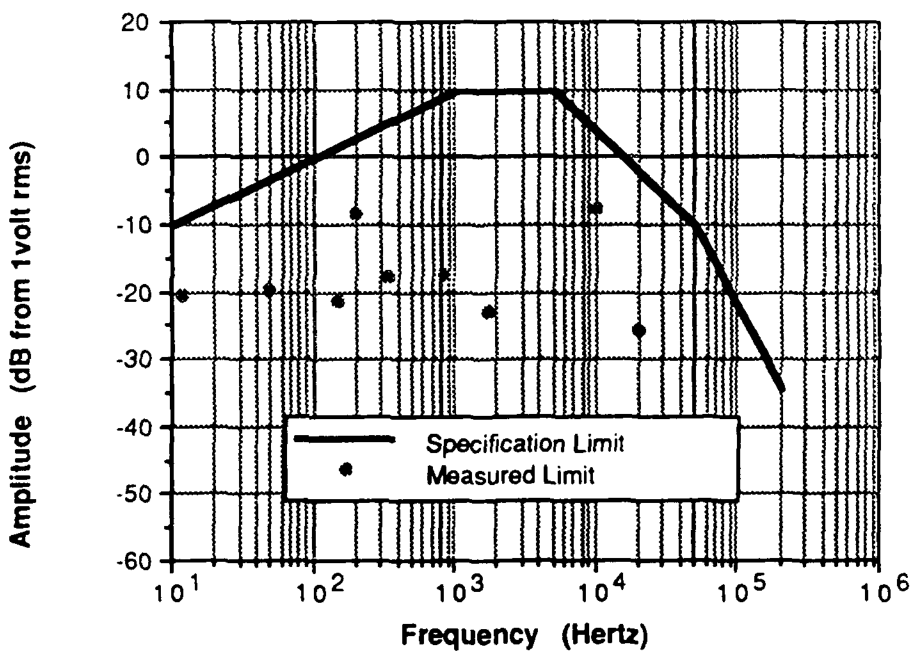

Distortion 17,000 rpm - No Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

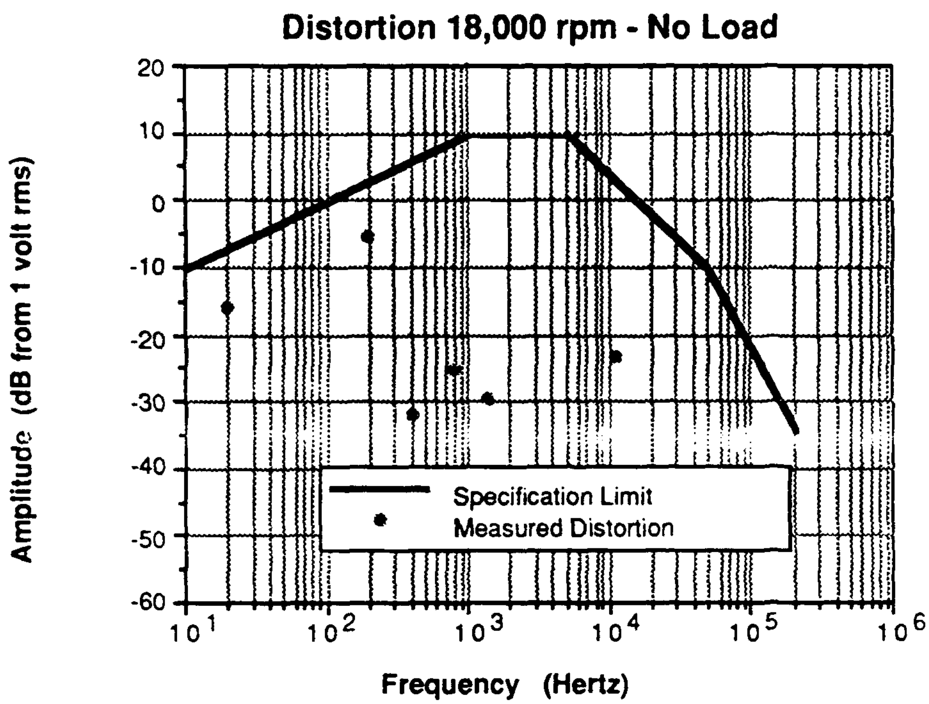

Distortion 17,000 rpm - 25% Load
Amplitude (dB from 1 volt rms)
20
10
0
-10
-20
-30
-40
-50
-60
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

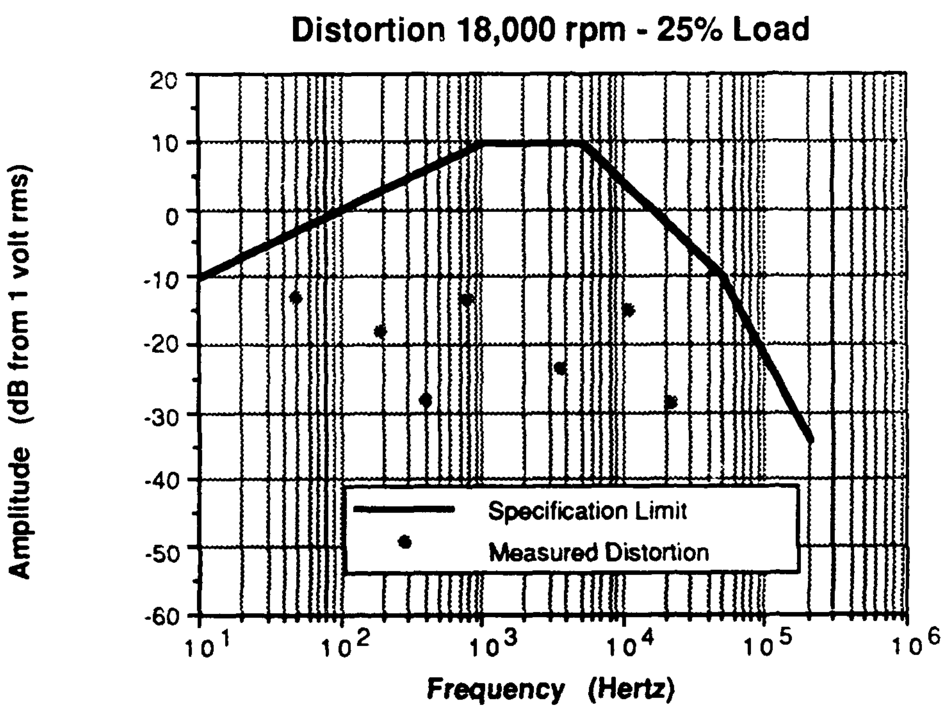
Distortion 17,000 rpm - 50% Load



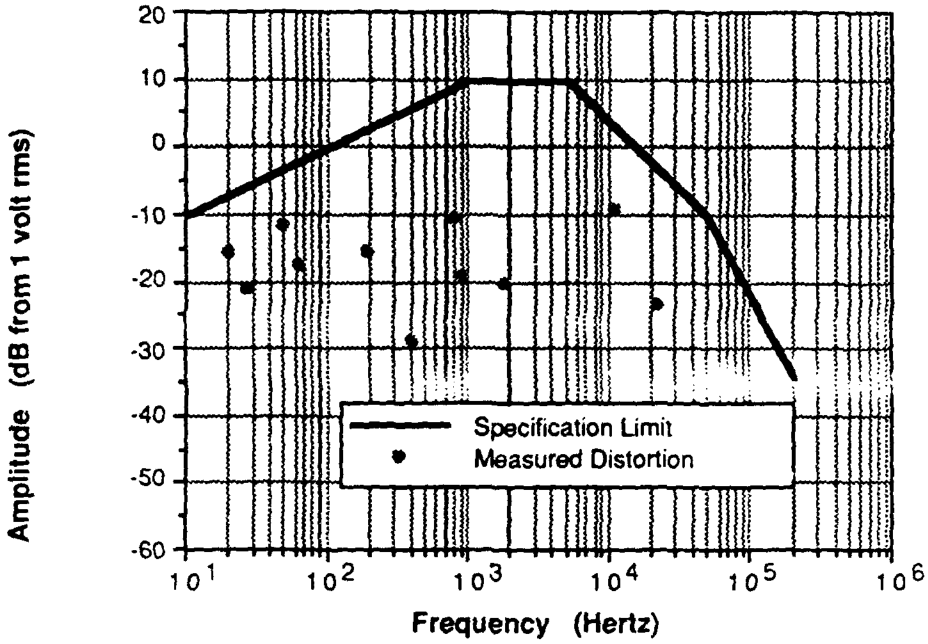
Distortion 17,000 rpm - 75% Load




Distortion 18,000 rpm - No Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)


Distortion 18,000 rpm - 25% Load
20
10
0
-10
-20
-30
-40
-50
-60
Amplitude (dB from 1 volt rms)
Specification Limit
Measured Distortion
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hertz)

Distortion 18,000 rpm - 50% Load



Distortion 18,000 rpm - 75% Load